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CITRUS CHLOROSIS AS AFFECTED BY IRRIGATION AND FERTILIZER TREATMENTS

By P. S. Burgess and G. G. Pohlman

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CITRUS CHLOROSIS AS AFFECTED BY IRRIGATION AND FERTILIZER TREATMENTS

By P. S. Burgess and G. G. Pohlman

INTRODUCTION

Citrus trees have been grown successfully in Arizona for more than 40 years. The first commercial grove was planted at Ingleside in the Salt River Valley during 1889 by W. J. Murphy and consisted of 20 acres of orange and lemon trees which had been imported from southern California. The success of the grove resulted in additional plantings in this district, until at present over 1,600 acres of citrus trees (about 250 in bearing) are to be found in this valley. On the Yuma Mesa the first orchard was set by H. W. Blaisdell in 1892 and also consisted of 20 acres of oranges and lemons. It has been followed by other local plantings, until at present approximately 700 acres (about 130 in bearing) have been planted, largely to grapefruit. It is not the writers' purpose to give a detailed history of the citrus industry of this State. This has been done by Coit * and, more recently by Shamel, Pomeroy and Caryl.† Suffice to say that these early plantings were remarkably free from diseases and, except where water shortages occured, were very successful. On the whole, matters went well with the growers of both districts until about 10 years ago when certain of the older groves began to show signs of deterioration. This was manifested by lessened yields, usually accompanied by a yellowing of the foliage and the presence of unusual amounts of dead and weak wood. At first the trouble was not general but was confined to small

* Citrus culture in the arid southwest, by J. E. Coit, Ariz. Agr. Expt. Sta. Bul. No. 58 (1908).

† Citrus fruit growing in the southwest, by A. D. Shamel, C. S. Pomeroy, and R. E. Caryl, U.S.D.A., Farmers' Bul. No. 1447 (1925).

areas (often one or two trees) in a particular orchard. However, conditions gradually became worse until in 1923, at the request of the Secretary of the Arizona Citrus Growers' Company, a survey of the groves in the Salt River Valley was made by Professors J. G. Brown, F. J. Crider, and C. N. Catlin of the Arizona Agricultural Experiment Station, and reports submitted.

This survey consisted of a pathological study of the trees in eight diseased areas, together with analyses of the soils, an examination into tillage, irrigation, and fertilizer practices and, in so far as possible, information concerning the kinds and sources of buds and rootstocks used. The final conclusions of the plant pathologist were that chlorosis and a variety of dieback were fairly prevalent, while mottle-leaf, brown-rot gummosis, California scaly bark, and fungal leaf-spot were occasionally present but not in menacing amounts. The experiment station horticulturist found that the groves most seriously affected were from 20 to 35 years old and had on several occasions suffered severely from water shortage before the completion of the Roosevelt Dam. Those showing the greatest damage had, for years at a time, been in permanent sod, originally alfalfa, but later wild grasses and weeds. Such conditions often had caused shallow rooting and, when finally plowed, this operation had brought about serious disturbances of the root systems. Most of the older groves, furthermore, had been planted on virgin or fairly new desert lands, very low in nitrogen and organic matter and, until recently, little consistent effort had been made to improve fertility conditions. In some cases the land had not been leveled properly before planting which caused over- and under-irrigated areas. Rodent damage was frequently noted as was also frost damage. The root systems of three unhealthy trees, at the time the survey was made, showed nothing abnormal when compared with those of healthy trees. Recommendations consisted of the removal of badly affected trees; in-arching the more vigorous; releveling the land where possible; rodent control; systematic pruning, and proper cultivation and fertilization. The studies of Mr. Catlin were confined to chemical analyses of the soils, especially as regards their nitrogen, calcium carbonate, organic matter, and alkali-salt contents. Soil profiles and field-moisture conditions were also studied in three groves. The results of this work indicated that the soils were very low in total nitrogen and organic matter; that calcium carbonate was not present in excessive quantities; that the amounts of alkali salts were usually too small to be toxic; that subsoil conditions varied greatly from hardpan to extreme coarseness in certain

instances; and, that more attention should be given to an equal distribution of irrigation water. Final reports on this Salt River Valley citrus survey were submitted during December, 1923, and with the exception of a few treatments applied to some half-dozen trees in Mr. G. H. Libbey's grove, no further work had been attempted until the present writers began operations in the early spring of 1925.

While the above-mentioned survey was being made in the Salt River Valley, the Experiment Station received a request for similar assistance from Mr. David Aepli, Manager of the Yuma Mesa Orange Ranch at Yuma. This grove had been badly chlorotic for several years, yields had decreased, and conditions were bad. As a result of this request, Mr. Catlin made two or three trips to Yuma during November and December, 1923, and collected several series of soil samples down to a depth of 5 feet for chemical studies. One or two additional sets of samples were sent to the Experiment Station by Mr. Aepli during the following spring for moisture determinations. Until the inception of the detailed studies on the Yuma Mesa recorded herein nothing further had been done by the Experiment Station at Yuma.

During the first week of September, 1924, the senior author, accompanied by Dr. J. G. Brown of this Experiment Station visited the groves of Messrs. Silver, Travers, Miller, Diller, Armbruster, Goldbaum, Libbey, Murphy, and Thompson in the Salt River Valley. Certain of these groves were in good condition while others were decidedly chlorotic, showing much dead wood and yellowed foliage. The following week a similar survey was made of the Yuma Mesa groves. All of the younger plantings which had received proper attention appeared to be doing well. The older portions of the Blaisdell Grove (the Yuma Mesa Orange Ranch), however, showed advanced stages of chlorosis and die-back. A rather careful preliminary study of conditions in these two important citrus-growing districts of the State suggested that the present diseased appearance of certain of the groves might be due to entirely different causes.

As this bulletin deals largely with the chlorosis and die-back of citrus trees, a brief description of these diseases may not be out of place at this point. The term " chlorosis " is rather indefinitely confined to a fairly widespread physiological disease of plants whose visible indication is a yellowing or whitening of the leaves, denoting chlorophyll disintegration within the chloroplasts. Anything which prevents the formation of chlorophyll in the leaves of plants or interferes with its normal functioning, strikes directly at the carbohydrate food supply, and at once

results in a weakened, diseased condition. Trees thus affected yield poor crops of fruit of inferior quality. So far as plant pathologists have been able to learn, the malady is not caused by an outside, pathological parasite but is the result of some vaguely understood internal physiological disturbance or nutritional derangement. A number of unfavorable environmental conditions have been thought to cause citrus chlorosis. Among the more common may be mentioned the following: lack of available iron; deficiency or improper balance of potassium, magnesium, nitrogen, and sulphur within the soil solution; absorption of ammonia in excessive amounts by plants following heavy applications of manure to soils of low nitrifying power; improper drainage; poor soil aeration; presence of alkali salts; use of fertilizers not suited to citrus culture; an excess of calcium carbonate (lime) in the soil or subsoil; and large surpluses of nitrate-nitrogen at certain periods during the annual growth cycle.

"Mottle-leaf" has been considered by some to be a variety or kind of chlorosis. It is also a physiological disease and may be produced by certain of the causes enumerated above as well as by an excess of soluble potassium accompanied by low calcium concentrations in the soil solution. This malady is characterized by the formation of light-colored areas or spots between the veins of the leaves, which often enlarge until almost all of the leaves except the veins are mottled yellow or white. A serious lack of organic matter as well as excessive applications of highly-concentrated, soluble, commercial fertilizers have also been considered as causative agents.

Where the trees have been suffering from either chlorosis or mottle-leaf for any considerable period, a premature falling of the foliage usually results, especially at the tips of the branches which gradually die back from the ends. This occasions large amounts of dead and weak wood on the outside of the trees and gives them a brushy, unhealthy appearance. This condition may or may not be the true die-back, or citrus exanthema, but its effects are the same — small yields and poor quality of fruit.*

In planning the work hereafter discussed, it was decided to carry out a detailed physical, chemical, and bacteriological study

* A large amount of work has been done on the chlorosis or yellowing of plants and a very extensive literature is in existence concerning the possible causes. It is not the writers' intention, however, to attempt a review of this material which is often contradictory. Suffice to say that, with the exception of spraying with ferrous sulphate and manganese sulphate solutions in a few instances, few curative measures have proved permanently successful.

of the soils from certain of the poor groves followed by a carefully planned series of field soil-treatments.*

Later on a series of pot experiments with grapefruit seedlings in the greenhouse at Tucson was undertaken in an endeavor to answer certain questions raised by the field work regarding the potential effects of calcium carbonate on the production of chlorosis. Possible curative measures were also studied.

For the sake of clarity, a discussion of the work will be taken up under separate headings: first, the laboratory studies on the soils from (1) the Salt River Valley, and (2) the Yuma Mesa; second, the field-fertilizer studies in (1) the Salt River Valley, and (2) on the Yuma Mesa; third, the field-moisture studies; and, fourth, the pot-culture work in the greenhouse at Tucson.

LABORATORY STUDIES

Several series of soil samples were taken from each of the groves under experiment in 1-foot sections down to depths of from 5 to 8 feet for alkali determinations and also for the purpose of studying the physical texture and structure of the soil profiles. Total nitrogen, nitrate-nitrogen, total and water-soluble phosphorus, strong-acid-soluble and replaceable potassium, and the percentages of calcium carbonate were also determined in most of the samples drawn. The reaction (pH) of the soils and conductivity measurements of the soil extracts were also determined, as well as the moisture equivalents from which the wilting coefficients were computed, and the rates of water penetration as shown by percolation tests. The rapidity of nitrification (nitrate production) and the bacterial fixation of atmospheric nitrogen in the surface and second feet of most of the soils were also ascertained.

(A) SALT RIVER VALLEY SOILS

With the exception of the Heard grove, all of the citrus properties studied were on the north side of the Salt River in the Camelback Mountain district. In none of the groves studied had the trees reached such an advanced stage of chlorosis and dieback as to render them entirely barren, but in most cases the foliage had lost that bright, dark-green, healthy color which so

* The groves in which these treatments were installed were as follows: In the Salt River Valley: Those owned by G. H. Libbey, D. B. Heard, J. E. Thompson, and W. J. Murphy. On the Yuma Mesa: The Yuma Mesa Orange Ranch and the G. M. Hill grove. As the work progressed, moisture studies also were made on the Hopkins grove at Yuma and on the Yuma Mesa Grapefruit Syndicate property. Soil samples were also studied from the Avery, Miller, and Duckett groves near Phoenix and surface fertilizer treatments applied to the first two.

delights the grower's eye, and was light green to yellow in appearance with small leaves and poor fruit yields.

Practically all of the soils devoted to citrus culture in the Salt River Valley are located on a soil type classified by the United States Bureau of Soils as Maricopa Gravelly Loam, averaging approximately 20 percent of coarse gravel. The surface soil is usually a fine sand intermixed with gravel and underlaid at from 1 to 4 feet by still coarser materials, stones up to 2 inches in diameter being not uncommon. These soils are the first of the alluvial products deposited by flood waters from the mountain sides, and consist largely of granite debris. They extend some 2 miles out into the valley gradually merging into the Maricopa Sandy Loam series. Where the surface soils are shallow (1 to 2 feet deep) as is occasionally the case, the water-holding capacity of the root zone is low. This necessitates great care in irrigation. Frequent and light water applications are necessary where the water table is deep, but where it is within 8 or 10 feet from the surface, much less water should be used. An average mechanical analysis of the fine earth (less than 2 mm.) of the Maricopa Gravelly Loam as made by the United States Bureau of Soils is as follows:

Organic matter	1.85 percent
Gravel (2-1 mm.)	8.91 percent
Coarse sand (1-0.5 mm.)	8.50 percent
Medium sand (0.5-0.25 mm.)	9.51 percent
Fine sand (0.25-0.10 mm.)	14.64 percent
Very fine sand (0.10-0.05 mm.)	34.45 percent
Silt (0.05-0.005 mm.)	16.22 percent
Clay (less than 0.005 mm.)	5.46 percent

A sample taken from the F. W. Avery grove showed 64.6 percent coarser than 0.5 mm. in diameter and 35.4 percent finer. A chemical analysis of this soil (strong-acid-digestion method), compared with an average of six other analyses of the fine earth of the Maricopa Gravelly Loam appears in Table I.

These analyses do not take into consideration the gravel larger than 2 mm. in diameter, and since this fraction occasionally amounts to one-half of the entire weight of the soil, it will be seen that the total amounts of plant-food materials are actually present in much lower percentages than above shown, while *available* plant nutrients, if not actually deficient, must be present in very small amounts. Proper methods of fertilization thus appear to be of considerable importance on this general soil type. This should be especially true for the areas where shallow surface soils predominate.

TABLE I.— AVERAGE ANALYSIS OF MARICOPA GRAVELLY LOAM (FINE EARTH) COMPARED WITH THE SURFACE SOIL FROM THE AVERY GROVE.

Constituent	Average of six analyses of Maricopa Gravelly Loam — Percent	Avery soil Percent
Insoluble residue	72.35	73.02
Soluble silica (SiO_2)	10.29	9.58
Alumina (Al_2O_3)	4.94	4.76
Iron oxide (Fe_2O_3)	4.41	4.67
Lime (CaO)	2.07	1.35
Magnesia (MgO)	1.36	1.19
Potash (K_2O)	.66	.59
Soda (Na_2O)	.28	.25
Manganese oxide (Mn_3O_4)	.05	.07
Phosphoric acid (P_2O_5)	.09	.06
Sulphur trioxide (SO_3)	.03	.03
Carbon dioxide (CO_2)	.87	.21
Chlorine (Cl)	.03	.01
Nitrogen (N)	.04	.03
Humus (organic matter)	.51	.45

Alkali determinations were first made on the samples of soil taken from the Heard, Thompson, Libbey, and Murphy groves. They appear in Table II. The fine earth which passed a 2-mm. sieve only was analyzed, the stones and gravel being discarded. As will be seen, black alkali (figured as soluble carbonate) is not present in these soils, and in no case is white alkali found in injurious amounts.

TABLE II. – ALKALI SALTS IN SALT RIVER VALLEY CITRUS SOILS
(Parts per million of soil.)

HEARD GROVE

North End — Between trees 2 and 3.							South End — Between trees 22 and 23						
Ft.	Total solids	Ca	Mg	SO_4	Cl	HCO_3	CO_3	Ft.	Total solids	Ca	Mg	SO_4	Cl	HCO_3	CO_3
1st	1020	30	8	150	120	256	0	1st	1270	45	15	175	160	293	0
2nd	780	15	8	100	90	280	0	2nd	880	30	15	135	100	293	0
3rd	800	30	8	75	100	305	0	3rd	840	60	15	140	130	305	0
4th	700	30	8	50	110	305	0	4th	820	30	15	80	100	329	0
5th	730	30	15	100	130	250	0	5th	840	45	15	145	130	256	0
6th	840	15	8	75	110	268	0	6th	830	60	15	150	100	250	0
7th	780	30	8	75	150	256	12	7th	730	45	15	115	120	232	0
8th	710	30	8	60	80	268	12	8th	1110	45	15	175	90	220	0

TABLE II.—(Continued)

THOMPSON GROVE

East End — Row 8, tree 3								West End — Row 8, tree 23							
Ft.	Total solids	Ca	Mg	SO_4	Cl	HCO_3	CO_3	Ft.	Total solids	Ca	Mg	SO_4	Cl	HCO_3	CO_3
1st	1980	150	60	125	420	232	0	1st	1530	90	53	125	300	342	0
2nd	1250	90	30	140	270	232	0	2nd	1030	45	15	130	180	317	0
3rd	720	45	8	110	130	280	0	3rd	1110	45	8	140	190	317	12
4th	800	45	8	110	130	329	0	4th	990	60	15	125	200	293	0
5th	790	60	15	250	100	305	0	5th	760	60	15	120	130	293	0
6th	770	45	30	140	100	305	0	6th	650	45	8	115	90	305	0
7th	1140	75	53	115	100	256	12	7th	1080	45	15	110	90	305	12
8th	1120	75	38	125	50	293	12	8th	1500	45	15	110	160	293	0

LIBBEY GROVE

Ft.	Total solids	Ca	Mg	SO_4	Cl	HCO_3	CO_3
1st	920	30	15	120	130	390	0
2nd	1120	30	8	75	160	293	0
3rd	1060	45	15	140	250	280	0
4th	1250	75	15	140	400	280	0
5th	1240	15	8	115	370	378	0
6th	980	15	8	90	270	415	0
7th	850	15	8	130	150	329	0
8th	780	15	8	160	140	317	0

MURPHY GROVE

Ft.	Total solids	Ca	Mg	SO_4	Cl	HCO_3	CO_3
1st	1050	60	23	100	100	440	0
2nd	870	45	15	100	120	330	0
3rd	930	45	8	150	120	350	0
4th	1080	75	15	140	270	317	0
5th	1110	90	15	125	290	293	0
6th	1050	120	15	175	300	268	0
7th	1030	90	23	105	240	256	0
8th	1030	90	15	135	250	293	0

Table III presents data on the chemical composition of the several soils studied. The soils are all alkaline in reaction due to the percentages of free calcium carbonate shown in the last column. Total nitrogen is very low but the amounts of nitrate-nitrogen are in most cases sufficient, showing a high rate of nitrogen availability. Available potash (K_2O) as determined by the replacement method is sufficient in most cases although, where below 200 parts per million in the first foot, small applications of sulphate of potash might well be included in a fertilization program for this type of soil. The percentages of strong-

TABLE III.— CHEMICAL COMPOSITION OF SALT RIVER VALLEY CITRUS SOILS.

No.	Location of sample	Reaction pH	Total nitrogen percent	Nitrate nitrogen p.p.m.	Strong acid soluble potash percent	Replaceable potash p.p.m.	Total phosphoric acid percent	Water soluble—phosphoric acid p.p.m.	Calcium carbonate percent
1	Thompson, R.* 11 T.3 east, 1st ft.	8.12	0.032	40	0.544	188	0.146	13.0	0.75
2	Thompson, R.* 11 T.3 east, 2nd ft.	8.14	0.027	60	0.418	182	0.109	2.0	1.70
3	Thompson, R. 11 T.23 west, 1st ft.	8.12	0.033	15	0.515	213	0.131	13.0	1.22
4	Thompson, R. 11 T.23 west, 2nd ft.	8.10	0.023	25	0.428	184	0.119	2.0	2.42
5	Heard, R. 12 T.2 north, 1st ft.	8.22	0.039	8	0.502	310	0.161	41.2	1.00
6	Heard, R. 12 T.2 north, 2nd ft.	8.47	0.017	0	0.506	150	0.128	17.3	1.49
7	Heard, R. 12 T.23 south, 1st ft.	8.20	0.050	35	0.477	485	0.136	41.2	0.82
8	Heard, R. 12 T.23 south, 2nd ft.	8.50	0.021	2	0.407	164	0.088	17.3	1.50
9	Libbey, R. 7 T.26 west, 1st ft.	8.52	0.046	17	0.484	530	0.157	38.6	2.35
10	Libbey, R. 7 T.26 west, 2nd ft.	8.57	0.014	8	0.446	141	0.140	2.5	2.23
11	Libbey, R. 7 T.4 east, 1st ft.	8.33	0.048	10	0.391	194	0.185	38.6	2.60
12	Libbey, R. 7 T.4 east, 2nd ft.	8.55	0.024	0	0.434	116	0.137	2.5	2.33

* Thompson's grove, Row 11, Tree 3, east end of grove, 1st foot of soil.

acid-soluble potash are high in all cases when compared with soils of the East or Middle West but, due to a lack of sufficient amounts of decomposing organic matter in our soils, it does not always become available in sufficient quantities to supply a rapidly growing crop. However, when applied *alone* to our arid soils, potash has seldom paid for itself in increased crop yields. The total percentages of phosphoric acid are high which is commonly the case for arid, calcareous soils, but its availability is low. Soluble phosphoric acid was determined by repeatedly leaching the same 500 gm. sample of soil with four 500 cc. portions of pure water, analyzing each portion separately and adding all four determinations together. Equal amounts of the surface-foot samples from each grove were mixed, and analyses made on the composites. The same was done with the second-foot samples. Table IV shows the rates of solubility of phosphoric acid in these soils. The totals also are shown in Table III.

TABLE IV.—RATES OF SOLUBILITY OF PHOSPHORIC ACID IN SALT RIVER VALLEY CITRUS SOILS (Parts per million of soil).

Extraction	Thompson		Heard		Libbey	
	1st ft.	2nd ft.	1st ft.	2nd ft.	1st ft.	2nd ft.
1st	2.5	1.0	9.2	5.4	11.0	1.5
2nd	2.5	1.0	14.0	3.4	9.2	1.0
3rd	3.0	0	11.0	5.0	10.0	0
4th	5.0	0	7.0	3.5	8.4	0
Total	13.0	2.0	41.2	17.3	38.6	2.5

While a sufficiently rapid state of phosphate solubility is indicated for the surface soils of the Heard and Libbey groves, the Thompson grove might possibly respond to available phosphate applications. The soils from the second feet are without exception low in available phosphoric acid although deep plowing gradually should improve this condition. While applications of organic matter invariably increase phosphate solubility in acid or neutral soils they may have a reverse effect in alkaline soils carrying free lime carbonate.* Tests for available nitrogen

* See "The Availability of Phosphates in Calcareous or Alkaline Soils," by J. F. Breazeale and P. S. Burgess. Tech. Bul. No. 10, Ariz. Agr. Expt. Sta.

(nitrates), potash, and phosphoric acid were made on several other citrus soils from different parts of the Salt River Valley. The results usually showed fairly good nitrogen availability in spite of the fact that total nitrogen and organic matter were invariably low, high potash availability, and medium or low phosphoric-acid availability.

The chemical work above discussed, indicates that the following fertilizer program, if carefully adhered to, should give beneficial results. Heavy applications of organic matter (either manure or cover crops) should be turned under as deep as possible. The necessity for adding commercial-fertilizer nitrogen for citrus is doubtful where fairly heavy organic manuring is practiced. Soluble phosphates at the rate of 1,000 to 1,500 pounds per acre every 2 to 4 years should be broadcast and plowed under deep with the manure. The occasional application of sulphate or potash at the rate of 300 or 400 pounds per acre to heavy-bearing groves might prove beneficial. Young trees and those yielding medium or small crops probably are not limited by a deficiency of potash.

A series of soil-solution studies was also made on the surface soils from two good and two very poor citrus groves in the Salt River Valley. All of the soils were fine sandy loams of approximately the same moisture-holding capacities. We will designate the two good soils as A and B and the two poor soils as X and Y. The good soils were found to be much deeper than were those carrying the poor trees. The optimum moisture capacities for these soils were found to be about 18 percent. One and one-half kg. (about 3 lbs.) of each were made up to 12-percent moisture-content and packed into large glass percolating tubes. After standing 24 hours to come to approximate equilibrium, the aqueous soil solutions were displaced by ethyl alcohol, and analyzed with the results shown in Table V.

TABLE V.—ANALYSES OF SOIL SOLUTIONS FROM GOOD AND POOR SALT RIVER VALLEY CITRUS AREAS (Parts per million of soil solution).

No.	Total soluble salts	Ca	Mg	Cl	SO_4	NO_3	CO_3	HCO_3
A	2044	255	40	792	100	176	0	488
B	4730	480	96	1908	340	440	0	549
X	2328	330	96	540	100	572	0	488
Y	3710	540	128	936	180	792	tr.	670

An examination of these data is of interest. Nitrates are very high in all cases. Few producing citrus soils normally run much

above 20 p.p.m. of nitrates while here, calculated to a dry-soil basis, we have 22, 55, 71, and 99 p.p.m. for soils A, B, X, and Y, respectively. As is often the case, the poor soils are higher in nitrates, due to lack of crop withdrawal. Soils A and X, and B and Y are remarkably similar in solute content. From a chemical standpoint all should produce citrus about equally well. We must, therefore, look elsewhere for the differences in yields; either to age or variety of trees, previous irrigation or fertilizer treatment, or to physical soil conditions. As stated above, the good groves were both located on fairly deep soils, while the poor-soil areas were shallow and underlaid by strata of coarse gravel and stones.

The Salt River Valley citrus soils were examined also from a bacteriological point of view, being tested for their abilities to ammonify protein nitrogen, to nitrify ammonia nitrogen, and to fix atmospheric nitrogen. The samples were taken February 9 to 14, 1925, in 2-quart sterilized, glass jars, aseptic method of sampling being used. The incubation periods were as follows: for ammonification, 1 week; for nitrification, 4 weeks; for nitrogen fixation, 3 weeks. Moisture conditions were kept near optimum and a constant temperature of 27° C. was maintained. The results secured appear in Table VI. The locations of the samples are arranged in the same order as shown in Table III.

TABLE VI.—BACTERIAL ACTIVITY OF SALT RIVER VALLEY CITRUS SOILS.

No.	Ammonifying power	Nitrifying power		Nitrogen-fixing power	
		Percent $(NH_4)_2SO_4$ nitrified	Rating	Mgs. N. fixed	Rating
1	Fair	100	Good	9.5	Good
2	Fair	95	Good	8.8	Good
3	Fair	92	Good	9.5	Good
4	Poor	88	Good	8.7	Good
5	Good	96	Good	8.7	Good
6	Fair	90	Good	7.1	Good
7	Good	100	Good	8.7	Good
8	Fair	90	Good	7.0	Good
9	Fair	91	Good	9.3	Good
10	Fair	96	Good	9.0	Good
11	Fair	95	Good	9.0	Good
12	Fair	95	Good	9.0	Good

From the data presented in Table VI, it is evident that the soils examined are, in the main, sufficiently active biologically to warrant the opinion that no crop failure from this source is probable. The ammonia-producing organisms, for reasons not clear, are somewhat slower of action than are those of either of the other two groups. The reverse is usually true for humid

soils, although active nitrification is always to be preferred to too vigorous ammonification. The aerobic, nitrogen-fixing organisms are especially efficient in these soils, definite azotobacter membranes appearing on the surface of the mannite-solution cultures in 5 to 7 days after inoculation. Next to the last column in Table VI shows the amount of nitrogen fixed per gram of mannite oxidized. Quantities above 6 or 7 mgs. are well above the average and indicate the presence of a very active nitrogen-fixing flora. Taken as a whole, the bacteriological studies indicate a fair degree of biological activity and a generally healthy condition in this soil type which carries a very large per centage of the Salt River Valley citrus acreage.

In order that a better understanding may be had of the importance of bacteria and fungi to soil-fertility processes, let us digress for a moment and briefly discuss the part played by these indispensable allies of crop production. Our views of soil fertility have changed greatly during the past half-century. The science of bacteriology was in its infancy 40 years ago, and, with its rapid growth, our ideas of agriculture and soil science have broadened and expanded. Until comparatively recent times the soil has been regarded as being composed of dead vegetable and mineral matter, the changes occurring therein, as decay and putrefaction, being ascribed largely to chemical causes. Modern research has disproved many of these older conceptions. We now know that all arable soils literally teem with unseen life and that these minute living organisms are directly responsible for organic decomposition. The more life a soil harbors, the more fertile it becomes. This microscopic life consists chiefly of bacteria and molds.

There are several factors which affect the number of bacteria in a soil. Among the more important may be mentioned moisture, air, organic matter, mineral foods, acidity or alkalinity, and temperature. As a rule, sandy soils contain the fewest microorganisms, because of deficiency of organic matter and poorer water-holding capacity. However, if such soils are plowed deep and liberal amounts of green materials or manure are added, the bacterial content will be greatly increased. An ordinary sandy soil will often contain less than 100,000 bacteria per gram (about a level teaspoonful) but after some attention has been given to its cultivation, and fertilization, the count may increase to several millions per gram. In rich loam soils the numbers range from one to several millions, and even into the billions, due largely to the higher organic content which favors bacterial growth. In the heavy, compact adobe soils the bacterial count

is considerably less, due both to poorer aeration and to absence of sufficient organic matter. On the whole, it may be said that micro-organisms are most abundant in soils which are in the highest state of fertility, and as a rule, those soil conditions which are favorable to the growth of the higher plants are also well suited to the development of bacteria.

Bacteria are most numerous and active in the first foot of arable soils. Below 16 inches the numbers fall off very rapidly, until at 3 feet, in humid sections, the soil is practically sterile. The texture of the soil, however, makes considerable difference with reference to the lower limit, since with a more open, loose structure, organisms are likely to find their way to the lower levels. In irrigated regions bacteria frequently occur at depths greater than 3 feet, for it is not uncommon to find nodules on alfalfa roots produced by bacteria 10 feet down. In the more compact soils we find the lower limit of microbial activity much nearer the surface, since the conditions for aeration are poorer and the filtering action of the finely divided soil tends to prevent deep penetration.

For the sake of convenience in study, the soil bacteria are divided into six great groups, depending upon their functions in the soil. They are classified as follows:

1. The cellulose-destroying bacteria
2. The ammonifying bacteria
3. The nitrifiying bacteria
4. The denitrifying bacteria.
5. The nitrogen-fixing bacteria
6. The mineral-transforming bacteria

We will briefly discuss these six groups separately.

The Cellulose-destroying Bacteria.—The cell walls of plants are made up almost entirely of cellulose, which is a very inert substance. It is very resistant to solution and hydrolysis. For this reason much of manure is cellulose. Enormous quantities of carbon are locked up each year by the growing trees and plants, and were there no agents to liberate it as carbon dioxide from dead organic matter, it has been calculated that all of the carbon dioxide now in the atmosphere and that set free normally each year by combustion and respiration would be used up by growing vegetation within less than 70 years. We know that animal respiration and combustion supply about one-tenth of the carbon dioxide in the air, whereas bacterial decomposition of organic matter in soils supplies the other nine-tenths. Careful experiments have shown that over 12,000 pounds of carbon

dioxide are given off each year from 1 acre of fertile soil, and that this is brought about chiefly by the destruction of cellulose in that soil by the cellulose-destroying bacteria. These organisms do this by the excretion of the enzyme *cytase*, which has the power of breaking down the complex cellulose molecule into carbon dioxide and water. Those organisms also decompose the starches, sugars, and woody fibers of plants with similar results.

Bacteria and Soil Nitrogen.—We will now take up the four groups of bacteria which are responsible for the fortunes of soil nitrogen, and which, numerically, constitute over 80 percent of the soil's bacterial flora. There are over 70 million pounds of free-nitrogen gas in the air over every acre of land. Nitrogen is, nevertheless, the limiting element of crop production in most agricultural soils. There are several reasons for this: first, organic matter or humus is the chief primary source of this element, and it is often lacking in sufficient amounts; second, nitrates and ammonia, formed from the decay of this organic matter by bacterial agencies, are the only two forms of nitrogen which have been actually proved to be of direct use to plants, and these are readily lost, the nitrates by leaching, and the ammonia, being a gas considerably lighter than air, by volatilization; third, organic matter is often lost from the soils of arid regions by a purely chemical oxidation or slow burning where near the surface and dry; fourth, in poorly aerated or water-logged soils, the denitrifying bacteria (which will be mentioned later) liberate much nitrogen as the oxides of nitrogen and as free-nitrogen gas.

Combined nitrogen costs from 20 to 25 cents per pound and is often added to the soil in stable manure, green manure, dried blood, tankage, cottonseed meal, etc. The approximate pounds of nitrogen per ton of each of these materials are:

	Pounds per ton
Barnyard manure	15-30
Alfalfa hay (green)	15-18
Red clover (green)	10-12
Dried blood	260
Tankage	160
Cottonseed meal	100

In these materials the nitrogen is entirely in the form of protein, which, before it can be used by growing plants, must be changed to ammonia and nitrates by soil bacteria. Ammonification is the name applied to the first step in this transformation, and may be defined as the breaking down of proteins by bacteria and molds, one of the final end-products of which is ammonia

gas. This is accomplished by proteolytic enzymes which these organisms secrete. The ammonifiers are the largest single family of soil bacteria, both in point of numbers and also of species. In acid soils molds are often responsible for a part of this ammonia production.

As soon as ammonia is produced in the soil it combines with the carbon-dioxide-saturated water usually present to form ammonium carbonate. We know that this compound is an available source of nitrogen for some plants, as rice and potatoes, but most crops are unable directly to use ammonia nitrogen profitably. It is here that the nitrifiers step in and oxidize the nitrogen of the ammonium carbonate to nitric acid, or nitrates, the final end-product, which all plants can use directly as food. Nitrification is brought about in two distinct stages and by two entirely different species of bacteria. The nitrite bacteria oxidize ammonium carbonate to nitrous acid and nitrites, but can go no further. The nitrate bacteria here take up the work and complete the oxidation to nitric acid or nitrates. Nitrification may properly be defined as that process by which ammonium carbonate is oxidized to nitrate by the action of the nitrifying bacteria. This is distinctly an aerobic process, an excess of oxygen being required.

Denitrification is the reverse of nitrification. The denitrifying bacteria reduce the nitrate, either applied to the land as fertilizer, or formed by the nitrifying bacteria, to ammonia, the lower oxides of nitrogen, or in some cases to free-nitrogen gas. They are inimical to a soil's fertility. It is indeed fortunate that these bacteria are chiefly species which require anaerobic conditions, as these are seldom found except in poorly-aerated, water-logged, heavy soils. We thus feel confident in saying that large losses of nitrate-nitrogen do not occur through denitrification in properly-drained, properly-cultivated arable soils.

We now come to the two large groups of nitrogen-fixing bacteria. Up to this time we have discussed the *transformation* of nitrogen compounds only, and we have seen that there is much *loss* of nitrogen through leaching, volatilization, and denitrification. Were there no natural processes by which these losses of combined nitrogen could be made good, all of the combined nitrogen of soils would in a short time be lost. But there are two classes of soil bacteria which have the power of taking up the gaseous nitrogen from the air and building it into proteins within their own body cells. These two kinds of nitrogen-gathering bacteria are, first, those which live in the soil itself independently of the presence of growing plants; and, second, the bacteria

which live in the nodules on the roots of leguminous plants. There are two species of these free-living nitrogen-fixers which do not live on the roots of legumes. The anaerobic forms, whose chief member is *Clostridium pasteurianum*, live principally in the lower strata of the soil (between the second and fourth feet), where the supply of oxygen is very limited. It is the aerobic forms, the *Azotobacter* species, living chiefly in the surface 6 to 8 inches, which are the most important of these two classes. The first member of this interesting group, *Azotobacter chroococcum*, was discovered in 1901. Since then five or six other varieties have been added to this species. These aerobic forms fix from eight to twelve times as much nitrogen per unit of carbohydrate (which they use as food) as do the anaerobic species. There are several soil conditions which must be correct for nitrogen-fixation to take place. A supply of decomposing organic matter is essential since carbon is the source of energy for this class of bacteria. Without it there will be no fixation. A slightly alkaline reaction of the soil, thorough aeration, and proper temperature and moisture conditions are other desirable factors. One of the beneficial effects of fallowing land is due to these nonsymbiotic nitrogen-fixers. The following figures show in pounds per acre per year, the amounts of nitrogen which simply fallowing the land will add. The first two figures come from the Rothamsted Experimental Station in England:

100 lbs. N. per acre, Broadbalk field
25 lbs. N. per acre, Geescroft field
175 lbs. N. per acre, Minnesota Experiment Station

The symbiotic, nitrogen-fixing bacteria are those which live in the nodules found on the roots of leguminous plants. These bacteria obtain their carbohydrate food supply from the growing plant, while the plants in return acquire their soluble nitrogen from the bacteria. These have previously procured this nitrogen from the outside soil air, and transformed it into soluble protein forms available to the growing plant. We are at present sure of eight or nine separate strains of the nodule organism, all of which are dissimilar and each able to infect and produce nodules on a few different kinds of legumes only. More plainly stated, each legume has its own specialized strain of bacteria which alone is able to produce nodules on its roots. Most of the nodules are formed within the surface-foot of soil. There are certain soil conditions which are essential to the successful growth of legume cover crops. The more important are: a neutral or slightly alkaline reaction of the soil, since the bacteria which enter the roots of the legumes, produce nodules and event-

ually fix free nitrogen, cannot live and properly function in an acid soil. The fixation of nitrogen is distinctly an aerobic process. The soil should thus be in good tilth and well drained. The proper strain of bacteria must be present to inoculate thoroughly the roots of the legume chosen for the cover crop. The nitrogen in green legumes is more available than is that from other green plants, as it has been shown that the ammonifying and nitrifying bacteria are more easily able to transform it into nitrates. The amounts of nitrogen fixed per acre by an average leguminous crop are as follows:

	Per acre	Experiment station where tested
Crimson clover	250 lbs. N.	New Jersey
Crimson clover	188 lbs. N.	Delaware
Velvet beans	213 lbs. N.	Alabama
Velvet beans	172 lbs. N.	Louisiana
Velvet beans	141 lbs. N.	Florida
Alfalfa	160 lbs. N.	Illinois (last cutting only plowed under)

An average of all legumes from 16 state experiment stations where tests have been made, gave 122 lbs. of nitrogen added per acre per crop. We thus see that, while there are many losses of nitrogen from soils, there are always present agents which, where conditions are favorable, provide for the maintenance of a proper balance of this important plant-food element.

Relation of Bacteria to Minerals.—There are four ways in which acids are formed in soils:

1. The cellulose-destroying and ammonifying bacteria produce organic acids.

2. The nitrifying bacteria produce nitric acid.

3. Carbon-dioxide-saturated water gives us carbonic acid.

4. The sulphur-oxidizing bacteria, *Beggiotoa* and *Thiothrix*, produce sulphuric acid from the hydrogen sulphide given off by the ammonifying bacteria upon the decomposition of the protein molecule.

These acids acting upon the soil minerals slowly dissolve and render them available to growing plants. The potassium is usually changed to the carbonate, nitrate, or sulphate; the lime and magnesium to the nitrate or bicarbonate, while the phosphorus is usually taken up by the plant as the acid phosphate of calcium or potassium. Iron may enter the plant as a soluble organic compound.

Such improvements in methods for the bacterial examination of soils have been made in the past few years that at present we may study with a considerable degree of accuracy the relationships between bacterial activities and crop-production. Thus the ammonifying power, the nitrifying power, and the nitrogen-fixing power of soils as today determined, together with other chemical determinations, give us a very good indication as to a soil's probable fertility.

(B) YUMA MESA SOILS

The Yuma Mesa citrus district was first visited on September 8 and 9, 1924, and a preliminary survey of the Yuma Mesa Orange ranch, the Hill grove, the Hopkins, grove, and the young 200-acre planting of the Yuma Mesa Grapefruit Syndicate was made. The Yuma Mesa Orange ranch (also known as the "Old grove" and the "Blaisdell orchard") is from 30 to 35 years old while the other groves are all 10 years old or less. Large areas of the former (which comprises 60 acres) were in poor condition. The leaves were yellow and much dead wood was in evidence. The younger groves appeared healthy, although a few trees were somewhat backward in rate of growth and the foliage was light colored.

A detailed discussion of the soils of the Yuma Mesa will not be given here, since this can be found in Arizona Station Bulletin No. 89 entitled "The Yuma Mesa" by Vinson, Crider, and Thompson. Suffice to say that it is classified by the United States Bureau of Soils as Yuma Sand, is of a highly calcareous nature, and varies in texture from a coarse to a very fine sand. The Mesa rises abruptly about 90 feet above the Colorado River Valley and stretches as a flat plane eastward 20 miles to the Gila Mountains and southward into Mexico. The soil is very deep (80 to 100 feet) and at various depths horizontal bands of stiff clay are occasionally encountered. These bands vary in thickness from a fraction of an inch to several inches, the thinner layers predominating. There is practically no difference in appearance between the surface soil and the subsoil strata. In chemical composition the sands vary but slightly, being high in calcium carbonate and strong in acid soluble and available potash, fair in total phosphoric acid, but low in available phosphoric acid, and very low in organic matter and nitrogen. Except where underlaid near the surface by these clay strata, drainage is good and the soils are generally free from toxic amounts of the alkali salts. A general view of the Yuma Mesa before reclamation is shown in figure 1.

Fig. 1.— Yuma Mesa before reclamation.

The water used for irrigation purposes comes from the Colorado River and is pumped from the high-line valley ditch which runs north and south along the foot of the Mesa to the west. For the past several years, samples of the Colorado River water have been taken weekly at Yuma for analysis. From this data we find that the water carries an average of 0.57 percent silt or 5½ tons per acre-foot, 325 p.p.m. of calcium sulphate or 878 pounds per acre foot, 22 p.p.m. of potash or 60 pounds per acre-foot, 100 p.p.m. magnesium sulphate or 270 pounds per acre-foot, and 0.8 p.p.m. nitrate-nitrogen or 2.2 pounds per acre-foot. The amounts of soluble phosphate are negligible. Replacement studies showed the silt to carry 0.259 percent of replaceable calcium, 0.054 percent of replaceable magnesium and no replaceable sodium or potassium. During the summer and fall months (June 1 to November 1), the silt present averages 0.83 percent. From these figures it has been computed that about one-fourth of an inch of solid silt * is deposited on the land for each 5 acre-feet of water applied. On the soils of the "Old grove" this gradual deposition has been operative for many years so that at present the silt-blanket averages 14 or 15 inches in thickness over the entire planting. When the first survey of this property was made, a lack of proper root aeration which must obtain below the silt layer suggested itself as at least playing a part in the

* In reality this material is about 45 percent clay and 55 percent silt. When wet it runs together and is very sticky and when dry it is very hard and cracks badly.

poor condition of the trees. Percolation studies in the laboratory, using both air and water, later verified this opinion. Possible means of coagulating this silt-blanket were thus attempted. Portions of the silt in percolation tubes were treated with gypsum, calcium chloride, magnesium sulphate, aluminum sulphate, and sodium sulphate in different amounts (from 0.2% to 1%) and percolated with water. Three series of tests were made, the amounts of percolate coming through at the end of 48 hours indicated the degrees of coagulation. The results of the last series of tests are shown in Table VII. At the end of the 48-hour percolation period these soils were removed from the tubes, air-dried, reground, sifted, returned to the tubes and again percolated with pure water.

TABLE VII.—THE COAGULATION OF YUMA SILT BY DIFFERENT SALTS.

Salt	Percolate coming through in 48 hours	After drying out, percolate coming through in 6 days
Percent	cc.	cc.
0.2% $CaSO_4$	35	120
.4% $CaSO_4$	27	120
.6% $CaSO_4$	28	105
.2% $CaCl_2$	30	92
.4% $CaCl_2$	35	100
.6% $CaCl_2$	38	95
.4% $Al_2(SO_4)_3$	33	130
.6% $Al_2(SO_4)_3$	52	110
.8% $Al_2(SO_4)_3$	60	115
.6% $MgSO_4$	18	80
.6% Na_2SO_4	7	40
Check	18	60

The calcium salts and aluminum sulphate approximately doubled the rates of percolation. As a result of these experiments it was decided to make field applications of these materials in an endeavor to coagulate the silt-blanket and thus aerate the subsoil strata. A discussion of this work appears on page 213 of this bulletin.

The amounts of alkali salts present in the soils of the several groves studied appear in Table VIII.

As will be seen from these data, the Yuma Mesa soils are generally low in soluble salts except gypsum, although, as the last analysis in Table VIII shows, occasionally small localized areas appear where alkali concentrations are high. Little trouble is usually experienced, however, in leaching such areas free from

salts as the Colorado River water is of excellent quality for irrigation purposes and drainage is good. Many alkali determinations not shown in Table VIII have been made from time to time on soils from the "Old grove" and from the different 10-acre

TABLE VIII.— ALKALI SALTS IN YUMA MESA CITRUS SOILS.

Location of sample	Depth foot	Parts per million of soil						
		Total salts	Ca	Mg	Cl	SO_4	CO_3	HCO_3
Virgin Yuma Mesa Desert soil. East of "Old grove"	1st	370	15	7	20	Tr	0	317
Same	2nd	280	Tr	0	20	Tr	0	305
Same	3rd	510	15	7	80	125	0	146
Same	4th	390	30	0	30	75	0	207
Same	5th	300	Tr	0	40	Tr	0	232
Same	6th	260	Tr	0	10	Tr	0	146
"Old grove" east end middle block	1st	2130	195	22	140	325	0	671
Same	2nd	660	30	7	40	90	0	183
Same	3rd	330	Tr	0	10	Tr	0	171
Same	4th	420	30	7	20	Tr	0	183
Same	5th	440	Tr	7	20	Tr	0	110
Same	6th	260	Tr	0	20	Tr	0	195
Hopkins grove	1st	510	15	15	30	80	Tr	171
Same	2nd	430	30	15	20	Tr	Tr	180
Same	3rd	500	15	7	30	125	Tr	159
Same	4th	530	7	0	30	Tr	36	159
Hill grove — east end	1st	416	30	0	40	Tr	0	195
Same	2nd	301	Tr	7	30	Tr	0	157
Hill grove — west end	1st	419	Tr	7	30	Tr	0	171
Same	2nd	333	Tr	7	30	Tr	0	159
Syndicate grove No. 4	1st	394	30	0	30	Tr	0	207
Same	2nd	1066	75	15	260	Tr	0	378
Same	3rd & 4th	834	30	7	80	Tr	0	439
Syndicate grove No. 7	1st	610	15	15	20	Tr	0	256
Same	2nd	340	15	0	30	Tr	0	183
Same	3rd & 4th	280	0	0	20	Tr	0	146
Alkali spot near Hill's grove	1st	15470	375	131	6970	1085	Tr	97

TABLE IX. CHEMICAL COMPOSITION OF YUMA MESA CITRUS SOILS.

No.	Location of of sample	Reaction pH	Total nitrogen percent	Nitrate nitrogen p.p.m.	Total potash percent	Replaceable potash p.p.m.	Total phosphoric acid percent	Water soluble phosphoric acid p.p.m.	Calcium carbonate percent
1	Old grove 1st ft. middle block east	8.40	0.076	10	—	336	—	13.6	6.10
2	Old grove 2nd ft. middle block east	8.72	0.009	3	0.129	72	0.043	Tr.	7.30
3	Old grove, 1st ft. middle block, west	8.52	0.052	8	0.304	264	0.190	13.6	7.05
4	Old grove, 2nd ft. middle block, west	8.68	0.019	2	0.117	112	0.132	Tr.	5.25
5	Old grove, 1st ft. south block, west	8.50	0.056	7	0.670	H_2O sol. K_2O 28	0.125	14.4	7.05
6	Old grove, 2nd ft. south block west	8.62	0.014	1	0.107	27	0.044	Tr.	9.17
7	Old grove, 1st ft. south block, east	8.43	0.068	5	0.708	30	0.157	14.4	5.50
8	Old grove, 2nd ft. south block east	8.70	0.009	2	0.188	32	0.050	Tr.	3.77
9	Hill's grove, 1st ft. east end	8.89	0.012	7	0.139	13	0.079	5.0	2.92
10	Hill's grove, 2nd ft., east end	9.00	0.003	1	0.139	12	0.055	Tr.	2.66

blocks of the Yuma Mesa Grapefruit Syndicate's 200-acre planting, but all have shown salt concentrations of low magnitude. Thus, little trouble may be anticipated on the Yuma Mesa from alkali or high, water-table conditions.

The data in Table IX give a general idea of the chemical composition of the Yuma Mesa soils. All of the soils are distinctly alkaline, averaging more than 5 percent calcium carbonate. Total nitrogen in all of the soils is very low although nitrates vary greatly. The samples whose analyses are shown in Table IX were taken on November 11, 1924, and represent minimum nitrate figures. Large numbers of nitrate determinations were made periodically in connection with the soil-moisture studies hereafter reported. These data will not be presented. Suffice it to say that the amounts often varied several hundred percent on successive samplings, depending upon the time of year, proximity to an irrigation, fertilization, and doubtless to other factors. The supplies of total and available potash in these soils should be ample for all crop needs, especially when supplemented by irrigation from the Colorado River water which adds this element in amounts equivalent to approximately 90 pounds of potassium sulphate for each acre-foot of water applied. Total phosphoric acid is present in fair quantities in the Colorado River silt but the Mesa sandy soils are deficient in it. The same is true for avaliable (water soluble) phosphoric acid. Nemic * states that where water-extractable phosphoric acid falls below 15 p.p.m., practically all crops respond to soluble-phosphate applications, and where above 35 p.p.m., no response is usually shown. Water-soluble, phosphoric-acid determinations were made by Nemic's method and appear in the next to the last column of Table IX. As will be seen, the results are below the lower limit in all cases, indicating a very low state of availability. A 1-percent solution of potassium carbonate recently has been proposed as a solvent for the determination of available phosphoric acid in calcareous soils.† This method was also used. In each case, 200 grams of soil were shaken with 1 liter of the carbonate solution for 1 hour, filtered under pressure and an aliquot taken for analysis. The results of these analyses follow:

	p.p.m. available P_2O_5
Virgin desert surface soil (fine sand).....	11.4
1st ft. Old grove A (Colorado River silt)	81.1

* "A chemical method for determining phosphoric acid requirements of agricultural soils," by A. Nemic. In Compt. Rend. Acad. Sci. (Paris) 183 (1926) pp. 314-316.

† "The determination of available phosphoric acid of calcareous soils," by S. Das. India Dept. Agr. Mem., Chem. Ser. 8 (1926) No. 6.

2nd ft. Old grove A (Silt and sand) 20.4
6th ft. Old grove (Fine sand) 9.0
1st ft. Old grove B (Colorado River silt) 72.8
2nd ft. Old grove (Silt and sand) 39.0

This method shows the Colorado River silt to be fairly well supplied with available phosphoric acid while the sand is again shown to be very low.

In Hill's 30-acre grove will be found an area of possibly 1 acre which is typical of the "poor soil spots" occasionally encountered on the Yuma Mesa. The soil within these "spots" is a much finer sand, has little desert vegetation before reclamation, and takes water about one-third as rapidly as does the coarser, "good" mesa soil. Samples of the "good" and "poor" surface soils were obtained and the soil solutions, as displaced by alcohol, analyzed with the results shown below. It should be borne in mind that the soil from the "good" and "poor" parts of this grove have been treated the same, in so far as fertilizer and irrigation practices are concerned, over a period of 10 years.

	Parts per million of soil solution								
	Total salts	Calcium	Magnesium	Boron	Chloride	Sulphate	Carbonate	Bicarbonate	Nitrate
Good soil	700	22	4	1.6	28	150	0	259	9
Poor soil	3000	232	11	2.0	136	715	Tr.	610	160

From these figures it is evident that the soil solution is over four times as concentrated in the poorer, finer soil. The bulk of the solutes are gypsum and sodium bicarbonate, although chlorides and nitrates are both higher in the poorer soil. There has been recently considerable agitation in California regarding the toxicity to citrus of small amounts of boron compounds. For this reason, the amounts of boron in these soil solutions were determined and are presented in the table. It seems hardly probable that such low concentrations can be a dominating factor, for a number of determinations on different productive Arizona soils and irrigation waters show similar or larger amounts to be present.

A brief outline of the importance of soil bacteria to fertility processes appears on pages 195 to 201 of this bulletin. Certain of the Yuma Mesa soils were tested for ammonification, nitrification, and nitrogen-fixation by the direct-soil-culture method and by the solution-culture method. The samples were taken aseptically from the sides of trenches with flamed trowels and placed in 2-quart, sterilized, glass jars. The date of sampling was November 11, 1924. The incubation periods were the same as

for the Salt River Valley soils (see page 194). The bacteriological data appear in Table X.

TABLE X.— BACTERIAL ACTIVITY OF YUMA MESA CITRUS SOILS.

No.	Description of sample	Nitrifying power		N-fixing power	
		Percent $(NH_4)_2SO_4$ Nit.	Rating	Mgs. N fixed	Rating
1	1st ft. virgin desert soil	10	Very low	0	0
2	2nd ft. virgin desert soil	15	Very low	0	0
3	3rd ft. virgin desert soil	0	0	0	0
4	4th ft. virgin desert soil	0	0	0	0
5	5th ft. virgin desert soil	0	0	0	0
6	6th ft. virgin desert soil	0	0	0	0
7	1st ft. Old grove; middle block east	55	Fair	10	Good
8	2nd ft. Old grove; middle block east	5	Very low	0	0
9	3rd ft. Old grove; middle block east	0	0	0	0
10	4th ft. Old grove; middle block east	0	0	0	0
11	5th ft. Old grove; middle block east	0	0	0	0
12	6th ft. Old grove; middle block east	0	0	0	0
13	1st ft. Old grove; middle block west	65	Fair	10	Good
14	2nd ft. Old grove; middle block west	70	Fair	—	—
15	1st ft. Old grove; south block west	52	Fair	9	Good
16	2nd ft. Old grove; south block west	50	Fair	—	—
17	1st ft. Old grove; south block east	80	Fair	9.6	Good
18	2nd ft. Old grove; south block east	25	Low	—	—
19	1st ft. Hill's grove, north	15	Very low	8	Good
20	2nd ft. Hill's grove, north	10	Very low	0	0

The ammonification data are not shown since they were negative in the virgin soil and in the subsoil samples, and low in the surface soils. As with the Salt River Valley soils, ammonification is much lower than either nitrification or nitrogen-fixation. We cannot but emphasize the importance of fairly heavy manure applications to these sandy desert soils. They add not only organic matter as a source of nitrogen and of energy materials, but also large numbers of ammonia-producing bacteria as well. Probably this latter factor is of greater importance than is generally believed.

FIELD TREATMENTS

The object of the field treatments was to find, if possible, a practical method for combating citrus chlorosis and die-back by means of fertilizer treatments or the use of soil amendments. As a result of the chemical and bacteriological studies made on the soils from a number of the poorer groves, and reported in the preceding section of this bulletin, the following facts appeared evident. All of the soils were very deficient in organic matter and total nitrogen. Most of the soils studied carried fair amounts of total phosphoric acid, buts its availability was low. Potash, both total and available, was apparently present in adequate amounts. With the exception of ammonification, all of the surface soils were fairly active from a bacteriological point of view. The citrus soils of the Salt River Valley are occasionally shallow (1 to 3 feet underlaid by coarse sand and gravel), while those of the Yuma Mesa are all deep and fairly uniform in texture, except the Yuma Mesa Orange Ranch where the original fine sandy soil is overlaid by a layer of Colorado River silt which varies from 12 to 18 inches in thickness.

With these facts before us, a series of field treatments was made on certain of the poorer groves, using manure, commercial fertilizers, and, where the surface soils were heavy and poorly aerated, clay coagulants. The manure and most of the commercial fertilizers were applied as "deep treatments." This was done by digging circular trenches about 12 inches wide and 30 inches deep entirely around each tree at the outer drip of the branches, and filling them to a depth of from 8 to 12 inches with finely divided manure. The commercial fertilizers were uniformly distributed on top of the manure and a few shovelsful of surface soil added. The contents of the trenches were then forked over until thoroughly mixed, covered with surface soil, and irrigated sufficiently to saturate the buried materials. The surface fertilizer and clay-coagulant treatments were broadcast and harrowed in as deeply as possible. Spraying the yellowed foliage with solutions of iron and manganese salts was also tried, as this practice has resulted successfully in combating pineapple "yellows" in Hawaii and Porto Rico, in alleviating the chlorosis of grapevines in France, and in "greening up" chlorotic market garden crops, as spinach, lettuce, and beets, in Rhode Island and Kentucky.

In all of this work, the tree was taken as the unit. Each treated tree had a number painted on its trunk to avoid mistakes, and an accurate record of each was kept in a field notebook.

Untreated, similar-appearing trees in alternate rows were also numbered and used as checks. Different areas were used in all cases for the different treatments except where noted below. There follows a detailed discussion of the soil treatments employed together with dates of application. As a rule, fairly large amounts of the fertilizing materials were used so that there would be no doubt as to the direct cause in case beneficial results were secured.

(A) SALT RIVER VALLEY

Heard Grove.—Surface applications of clay-coagulating materials were made during February, 1925, as follows:

Aluminum sulphate	100 pounds	per tree	6 trees
Aluminum sulphate	300 pounds	per tree	6 trees
Magnesium sulphate	100 pounds	per tree	6 trees
Magnesium sulphate	200 pounds	per tree	6 trees
Gypsum	175 pounds	per tree	6 trees
Gypsum	350 pounds	per tree	6 trees
Inoculated sulphur	150 pounds	per tree	6 trees

On March 26, 1925, there was applied to one-half the above-noted trees the following fertilizer mixture as a surface treatment: 5 pounds "nitrogen mixture," * 5 pounds sulphate of potash, and 10 pounds double superphosphate per tree. At the same time in a different part of the grove the following "deep treatments" were made in trenches 30 inches deep, all of which first received 8 inches of finely divided manure in the bottom:

Nitrogen mixture	17½ pounds	per tree	5 trees
Nitrogen mixture	35 pounds	per tree	5 trees
Sulphate of potash	12½ pounds	per tree	4 trees
Sulphate of potash	25 pounds	per tree	4 trees
Double superphosphate	25 pounds	per tree	5 trees
Double superphosphate	50 pounds	per tree	5 trees
Double superphosphate and Nitrogen mixture	25 + 17½ pounds	per tree	5 trees
Sulphate of potash and Nitrogen mixture	12½ + 17½ pounds	per tree	5 trees
Sulphate of potash and double superphosphate	12½ + 25 pounds	per tree	5 trees
Ferrous sulphate	100 pounds	per tree	5 trees
Ferrous sulphate	200 pounds	per tree	5 trees

* The "nitrogen mixture" contained 3 parts sulphate of ammonia and 4 parts nitrate of soda by weight.

Besides the foregoing, five " deep treatments " without manure were given as follows:

Nitrogen mixture	35 pounds per tree	1 tree
Double superphosphate	50 pounds per tree	1 tree
Sulphate of potash	25 pounds per tree	1 tree
Sulphate of potash 25 and double superphosphate	50 pounds per tree	1 tree
Nitrogen mixture 35 and double superphosphate	50 pounds per tree	1 tree

During August, 1925, the following surface treatments were given to another part of the grove:

Sulphate of potash	8 pounds per tree	24 trees
Double superphosphate	8 pounds per tree	24 trees
Nitrogen mixture	8 pounds per tree	24 trees

About 6 weeks later these last treatments were repeated on the same trees.

Thompson Grove.— Surface applications of clay-coagulating materials were made during February, 1925, as follows:

Aluminum sulphate	50 pounds per tree	6 trees
Aluminum sulphate	150 pounds per tree	6 trees
Magnesium sulphate	50 pounds per tree	6 trees
Magnesium sulphate	100 pounds per tree	6 trees
Gypsum	85 pounds per tree	6 trees
Gypsum	170 pounds per tree	6 trees
Inoculated sulphur	75 pounds per tree	6 trees

In March, 1925, one-half of the foregoing trees each received the following as a surface treatment: 5 pounds nitrogen mixture, 10 pounds double superphosphate, and 5 pounds sulphate of potash. During February, 1925, the following " deep treatments " were made in trenches 30 inches deep, all receiving 8 inches of finely divided manure in the bottom:

Nitrogen mixture	9 pounds per tree	4 trees
Nitrogen mixture	17 pounds per tree	5 trees
Double superphosphate	12 pounds per tree	4 trees
Double superphosphate	25 pounds per tree	5 trees
Sulphate of potash	6 pounds per tree	5 trees
Sulphate of potash	12 pounds per tree	5 trees
Nitrogen mixture 9 and double superphosphate	12 pounds per tree	5 trees

Nitrogen mixture	9	
and sulphate of potash	6 pounds per tree	4 trees
Double superphosphate	12	
and sulphate of potash	6 pounds per tree	4 trees
Ferrous sulphate	50 pounds per tree	5 trees
Ferrous sulphate	100 pounds per tree	5 trees
Manure alone		5 trees

The following materials were applied in solution in 1-foot deep trenches without manure:

Copper sulphate (blue stone)	3 pounds per tree	5 trees
Manganous sulphate ($MnSO_4 \cdot 4H_2O$)	3 pounds per tree	5 trees

During August, 1925, the following surface treatments were given in another part of the grove:

Sulphate of potash	8 pounds per tree	30 trees
Nitrogen mixture	8 pounds per tree	30 trees
Double superphosphate	8 pounds per tree	30 trees

About 6 weeks later these last treatments were repeated on the same trees.

Libbey Grove.— During the first week in February, 1925, the following "deep treatments" were installed in trenches 18 inches deep in which were also placed about 5 inches of manure:

Ferrous sulphate	50 pounds per tree	6 trees
Double superphosphate	25 pounds per tree	8 trees
Double superphosphate	50 pounds per tree	8 trees
Sulphate of potash	$12\frac{1}{2}$ pounds per tree	8 trees
Sulphate of potash	25 pounds per tree	8 trees
Double superphosphate	25	
and sulphate of potash	$12\frac{1}{2}$ pounds per tree	8 trees
Manure alone		8 trees

Murphy Grove.— On January 23, 1925, the following "deep treatments" were made in 30-inch-deep trenches to which had been added about 4 inches of manure:

Nitrogen mixture	29 pounds per tree	4 trees
Nitrogen mixture	58 pounds per tree	4 trees
Double superphosphate	40 pounds per tree	4 trees

Double superphosphate	80 pounds per tree	4 trees
Sulphate of potash	22 pounds per tree	4 trees
Sulphate of potash	44 pounds per tree	4 trees
Manure alone		8 trees

(B) YUMA MESA

Yuma Mesa Orange Ranch.—The surface 12 to 18 inches of soil on this ranch is made up of the silt and clay from the turbid Colorado River water which here has been used for irrigation purposes over a period of more than 35 years. This surface layer is very heavy and intractable. The first treatments, made on December 15, 1924, were surface applications of materials which would coagulate and granulate this silt-blanket, thus accelerating moisture penetration and improving conditions for aeration. They were as follows:

Aluminum sulphate	100 pounds per tree	4 trees
Aluminum sulphate	200 pounds per tree	4 trees
Aluminum sulphate	400 pounds per tree	2 trees
Magnesium sulphate	100 pounds per tree	4 trees
Magnesium sulphate	200 pounds per tree	4 trees
Magnesium sulphate	300 pounds per tree	2 trees
Gypsum	175 pounds per tree	8 trees
Gypsum	350 pounds per tree	2 trees
Inoculated sulphur	100 pounds per tree	6 trees
Inoculated sulphur	200 pounds per tree	2 trees
Inoculated sulphur	300 pounds per tree	2 trees
Calcium chloride	100 pounds per tree	4 trees
Calcium chloride	200 pounds per tree	4 trees
Calcium chloride	300 pounds per tree	2 trees

These substances were broadcast in the square basins surrounding the trees out to the middles between the rows, disked in, and irrigated. During the following March, one-half of the trees receiving each of the above-mentioned treatments were given 5 pounds of nitrogen mixture,* 10 pounds double superphosphate, and 5 pounds sulphate of potash per tree. At the same time in a different block of trees the following "deep treatments" were installed in trenches 30 inches deep which received about 18 inches of corral manure (except where indicated) besides the commercial fertilizers as listed below:

* The nitrogen mixture contained 3 parts of sulphate of ammonia and 1 parts of nitrate of soda by weight.

Double superphosphate	25 pounds per tree	10 trees
Sulphate of potash	10 pounds per tree	10 trees
Nitrogen mixture	10 pounds per tree	10 trees
Double superphosphate and sulphate of potash	25 5 pounds per tree	10 trees
Double superphosphate and nitrogen mixture	25 5 pounds per tree	10 trees
Sulphate of potash and nitrogen mixture	5 5 pounds per tree	10 trees
Manure alone		5 trees
Sand alone (trench filled with Yuma sandy soil)		5 trees
Ferrous sulphate	50 pounds per tree	5 trees
Ferrous sulphate	100 pounds per tree	5 trees

After the materials had been thoroughly mixed, the trenches were filled to the top with the sandy, desert soil, and a heavy irrigation given.

Six months after the clay coagulants had been applied as surface treatments, samples of the surface-foot were taken where the heaviest applications had been made and, as a measure of relative permeability, the air-dried and sifted soils were placed in glass percolators and tested for rates of water percolation. The first 250 cc. of percolate which came through in each case were analyzed. The results of these tests appear in Table XI.

From the data in Table XI it appears that sulphur and gypsum are the best coagulants for the Colorado River silt, followed by aluminum sulphate, magnesium sulphate, and calcium chloride. Gypsum, due to its low price, would certainly be the material to use for this purpose. Certain of the trees receiving the heaviest applications lost a portion of their leaves. This was especially true of the calcium-chloride-treated trees. However, after the excess of these soluble materials had been removed from the soil by irrigation, new leaves were formed in all cases except where the largest amounts of calcium chloride had been used. Here the high concentration of chlorides killed the trees.

During the first 18 months after the above-mentioned field treatments had been installed in the Salt River Valley and on the Yuma Mesa, detailed tree records showing new leaf growth, general appearance, and fruit production were kept but, as very little differences developed between the treated trees and the checks, this mass of data will not be included in the report. Suf-

TABLE XI.— EFFECT OF CLAY COAGULANTS UPON PERMEABILITY OF YUMA SILT AND COMPOSITION OF PERCOLATES.

No.	Treatment	Rate per tree pounds	cc. of percolate after		Parts per million of soil					
			17 hrs.	40 hrs.	Ca	Mg	Cl	SO_4	CO_3	HCO_3
1	None	0	80	155	487	Tr.	105	958	0	775
2	Aluminum sulphate	400	160	365	1537	394	175	6262	0	420
3	Magnesium sulphate	300	175	285	1190	1293	210	8477	0	775
4	Sulphur	300	205	475	1537	825	210	7726	0	450
5	Gypsum	350	215	465	1537	319	210	5428	0	420
6	Calcium chloride	300	95	260	1650	56	2345	1627	0	900

fice it to say that none of the treatments except the "deep treatments" where both manure and double superphosphate were added, consistently showed improvement. Soluble phosphates and manure improved conditions somewhat but not markedly. At the end of the observation period, a number of the trenches were dug up. The manure had been partially decomposed but it was interesting to note that a complete network of citrus roots had filled practically the entire area occupied by the manure. In places the roots had formed a solid mat which was hard to break up with a spade. At the end of 2½ years the groves were again carefully inspected but still no pronounced differences in favor of the fertilized trees were evident. With one or two exceptions, the groves were in better condition than formerly but this statement applied to the untreated as well as to the treated sections.

Thus, while the fertilizer treatments involved much labor and expense, the results appear to have been largely negative. Although negative results are less valuable than positive results, they are useful in two ways. First, they point the way for future research, and second, they eliminate factors which otherwise might be considered as operative. For instance, here it is evident that the deterioration of these groves has not been due primarily to a lack of either organic matter or available plant-food materials, for these, when supplied in abundance, showed

little benefit over a period of 3 years. The same statement is true for the clay-coagulating materials where applied.

Five of the chlorotic trees at the Yuma Mesa Orange ranch were sprayed with a 2-percent solution of ferrous sulphate, five trees were sprayed with 0.1-percent solution of manganous sulphate, and five were sprayed with a mixed solution of the two salts. A slight "greening up" of all the sprayed trees was noticeable at first but the effects were not permanent.

FIELD MOISTURE STUDIES

We now come to a discussion of one of the most important parts of the work to be presented in this bulletin, for positive, beneficial results were secured. It has been known for several years that soil-moisture control in citrus groves pays. In fact, many of the growers in southern California pay a fair sum each year for such field-laboratory service, but up to the time this work was instituted, nothing had been attempted in Arizona along this line. Being well acquainted with both the work and the personnel of several of the field laboratories in California and realizing the marked benefit which many of the growers there had derived from this type of service, the senior author at the outset favored a careful soil-moisture control in the groves where the fertilizer treatments were installed, both in the Salt River Valley and on the Yuma Mesa. Later on this work was extended to include several other groves.

The importance of the need for greater efficiency in citrus irrigation cannot be over-emphasized for the damage done by over-irrigation and under-irrigation (usually the former), is heavy. In the growth of citrus in Arizona our experiments have shown intelligent irrigation to be of much greater importance than fertilizer practice, and this is being found to be true in California. In order to irrigate efficiently the grower must know the optimum moisture capacities of his soils and the wilting points, for between these two extremes lie the available water which his trees are able to use. In order to maintain proper moisture conditions within his soils with greatest economy he must know how often to irrigate, how best to apply the water, and how much water to use at each irrigation. In order to learn these facts he must first know soil conditions — depth, character, and rate of water penetration — and the feeding-root zone of his trees, for water must be supplied to this zone without allowing it to go far beyond. Water which goes below the root zone is not only wasted but it tends to raise the water table and to leach out

valuable plant-food materials. Of all these various factors, the two most important are *when to irrigate* and *how much water to apply*. Drainage systems seldom would be necessary if irrigation practices were correct, for very few of our orchards are located in alkali-soil areas where soil washing must be resorted to, and the waters used for irrigation are usually of good quality. At the present time three ways are used by growers in deciding upon the proper time for applying water: First, the "calendar method," which is all too common; second, the "guess method," where the grower picks up a few handfuls of soil from two or three places in his grove and feels of it; third, the systematic, soil-sampling method, where the soil from different depths are sampled and analyzed for their moisture content in a laboratory. The last method only is worthy of consideration for it alone places irrigation practice upon a scientific basis.

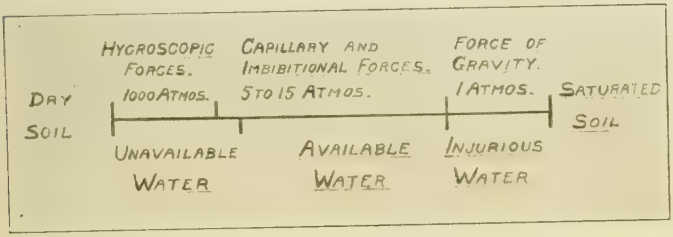


Fig. 2.— Physical divisions of soil moisture.

Before outlining the methods of moisture control used in our work, a brief discussion of soil and water inter-relationships may not be out of place. Soil moisture was early divided into hygroscopic, capillary, and gravitational, according as it is tenaciously held in the thin films about the soil particles by the force of adhesion, held against the force of gravity by surface tension in the capillary pores of the soil or freely moving under the action of gravity. This conception of soil moisture is shown in figure 2. Unless understood, this classification is unfortunate in that it suggests the existence of the soil water in three different chemical states which is not the case. This classification is one of forces, not of materials, and all of these forces affect either directly or indirectly all soil moisture. It might be better to drop the older terminology and consider the water as a unit, and speak not of hygroscopic, capillary, and gravitational water, but of the hygroscopic, capillary, and gravitational forces acting

upon this water. Let us discuss these forces or, to revert to the older terminology, "kinds" of soil moisture in some detail. Soils which are artificially dried so as to deprive them of all of their moisture, when exposed to moist air at first absorb water vapor with great avidity. Finally a state of equilibrium is reached for any given temperature and degree of humidity. At this point no more water vapor can be taken up by the soil under experiment. The smaller the individual particles of any soil the more water it will absorb from a saturated atmosphere due to its greater internal surface. It thus follows that sandy soils absorb the smallest amounts while clay soils and those containing much humus take up the most. All field soils when air-dry contain certain amounts of this hygroscopic water depending upon their texture, organic-matter content, and the temperature and the humidity of the air. We may define the "hygroscopic moisture coefficient" of any soil as the maximum percentage of water which it can absorb from a saturated atmosphere at a given temperature. These thin films of hygroscopic water are held very tenaciously (up to 1,000 atmospheres pressure) by the solid particles of the soil, and may be considered as the connecting link between the liquid water system and the solid framework of the soil. Hygroscopic water is unavailable to plants, although by preventing rapid and undue heating of the surface soil, it may be of indirect benefit. It should also be noted that it is within the hygroscopic water films that most of the mineral solvent action primarily occurs.

We now come to the most important physical form in which soil-water exists, for it is entirely from this fraction that land plants draw their necessary supply. This is the liquid water held by capillarity or imbibition within the pores of the soil against the force of gravity or within the sponge-like network of the soil colloids. This water moves either upward, downward, or laterally, independently of the force of gravity until uniformity of surface-tension is established, and this is seldom effected in fallow arable soils and never under a growing crop, for here the plants are continually drawing water from these capillary films. By interchange with the hygroscopic films the capillary water receives the necessary dissolved mineral constituents, thus serving as the vehicle of all food absorbed by the growing plant besides supplying moisture to sustain the enormous transpiration by which plants maintain during the hottest days a temperature sufficiently low to permit of proper photosynthesis. The capillary water would soon be exhausted were it not replenished. This is effected by the capillary rise of water from the

" groundwater " or " water table " into the root zone, by irrigation, or by natural rainfall.

In most cultivated soils the air spaces constitute from 35 to 45 percent of their total volume, and this space when filled with water represents the saturation point or the " maximum water-holding capacity." For the best development of plants it has been found that the soil moisture present should not exceed 60 percent of this " maximum water-holding capacity." This, for most soils will be found to closely approximate the sum of the hygroscopic and the capillary waters, and, as will be seen, leaves about 40 percent of the pore-space to be filled with air. This condition is usually termed the " optimum moisture-content " of a given soil.

Gravitational water is that portion of the soil moisture in excess of that held by hygroscopic and capillary forces, which is free to move under the influence of gravity. It is thus the difference between the " maximum water-holding capacity " of a soil and the sum of the other two forms, and is measured by the amount which will flow from a soil having all of its pores filled with water. The total drainage from a saturated piece of land would thus represent the gravitational water there present, and the plane in the soil at which all of the pores are permanently filled with water is spoken of as the " water table." Gravitational water is directly injurious to upland plants, but in the absence of alkali, when it exists at depths of 8 to 10 feet from the surface it is of untold benefit as a reservoir from which moisture is withdrawn and supplied to growing crops by capillarity. Some deep-rooted plants, as alfalfa and trees, often send down tap-roots to the water table when this is far below the point from which water can be raised by capillarity, but this is not the case with most crop plants. Figure 2 should make clear the divisions of soil moisture and that fraction which is available to ordinary vegetation.

From the foregoing discussion it must be evident that a mere statement of the *total moisture content* of a soil gives practically no information as to the amount of water which is available to plants growing upon that soil. To obtain such information it is necessary first to ascertain the percentage of water in the soil at the wilting point, and this may be calculated from the " moisture equivalent." This latter term may be defined as the percentage of water which a soil is able to retain against a centrifugal force one thousands times that of gravity, and is determined by spinning a known volume-weight of saturated soil in a motor-

driven, vertical centrifuge especially built for this purpose.* A series of careful studies by Briggs and Shantz † showed that this moisture equivalent bears a constant relationship to the wilting point of any given soil. They found that, if the moisture equivalent was divided by the factor 1.84, the resulting quotient closely represented the percentage of water in the soil when plants growing in it began to wilt. The wilting point for all plants in the same soil is identical, but it varies widely between soils of different texture — the finer the soil the higher the wilting point.

The citrus tree is naturally shallow-rooted. At least 75 percent of its feeding roots are usually located in the second and third feet of soil. In heavy adobe soils the roots are often massed in the surface foot, very few feeders going below 18 inches. Root distribution studies both in Arizona and in California are used as a basis for these statements. It is thus apparent that heavy irrigations where penetration goes far below the fourth foot, must entail a considerable waste of water. The frequency of irrigation is dependent chiefly upon soil and climatic factors. As a rule, in areas of high temperatures and drying winds, water must be applied more frequently but even here the soil is the dominant factor. While heavy soils retain more available water than do light ones, actual water movement toward the absorbing roots in the former is much slower. The rate at which heavy soils take water is also very much slower so that often the second and third feet receive little water from a 4- or 5-inch irrigation. Then again, the shallower root penetration into the heavier soil must be considered. With these facts in mind it is evident that, in the heavier soil types, the trees were forced to rely largely upon the water stored in the surface foot or two feet for its supply from one irrigation to the next, while in sandy soils, where easy root and water penetrations prevail, the water in the surface 3 or 4 feet may be readily available. Now where both types of soil occur on the same ranch, as is sometimes the case, a differential irrigation practice is essential for here the danger both from under-irrigation and over-irrigation is apparent where a uniform water application is given. Where these conditions are encountered, a systematic, laboratory moisture-control is the only safe procedure to follow.

The methods employed in our irrigation-control work were as

* "The moisture equivalent of soils," by L. J. Briggs and W. J. McLane. U.S.D.A. Bur. Soils, Bul. 45 (1907).

† "The wilting coefficient for different plants and its indirect determination," by L. J. Briggs and H. L. Shantz. U.S.D.A. Bur. Plant Indus., Bul. 230 (1912).

follows: The orchards are set in 10-acre blocks. If the soil was very uniform, two sets of soil samples were usually taken in each block, one near the center of the upper end and one near the center of the lower end.* Different ways of securing representative samples were tried. It was finally decided to take one set 4 feet deep on each of the four sides of the same tree just under the drip of the branches, keeping each foot-sample separate, then combine the four first feet for the first sample, the four second feet for the second sample and so on down for the 4 feet. There were thus four borings in each composite sample. On the Yuma Mesa the surface 6 to 10 inches dries out very rapidly after an irrigation. Moisture determinations on the first foot-samples were, therefore, omitted as very few feeding roots were present in this zone. Tin cans of proper size, provided with tight-fitting covers were used for collecting the samples and transporting them to the field laboratory. The cans were adjusted to equal weight for convenience in making the moisture determinations and were all numbered. A King soil-sampling tube (made of tool steel) and special hammer were used in taking the samples. An electric oven with thermostat control (100°C.) was utilized for drying the samples. Moisture-equivalent determinations were made on a representative series of soil samples from each location at the beginning of the work. From these the wilting points were calculated as explained above. The moisture data as secured were plotted on $8\frac{1}{2}$x14-inch coördinate paper and kept in a large, loose-leaf notebook. One page was used for each location. Lines showing the moisture equivalent (in green) and the wilting point (in red) were ruled across the page for each foot of soil profile. The moisture percentages determined at the different sampling dates were plotted on the abscissæ in black as they rose and fell with successive irrigations. The groves were sampled every 7 or 8 days, except during the winter months, when little irrigating was done. With this system kept up to date, anyone can tell by looking at the curves just where the orchard stands as regards moisture supply, just when it should be irrigated, and how much water should be applied to wet the soil properly to a depth of 4 or 5 feet.

All of the moisture data are plotted on the two loose sheets folded into the back of this bulletin. The heavy, horizontal lines indicate the wilting points for the soils of each foot. As will be seen, the work in the Salt River Valley was done in the Heard and Thompson groves, and on the Yuma Mesa in the South Block of the Yuma Mesa Orange ranch, Hill's grove, Hopkin's grove, and in blocks 4 and 18 of the Yuma Mesa Grapefruit Syndicate.

* In the average 10-acre block at least four sets of samples should be taken.

The groves in the Salt River Valley were not permitted to dry out nearly as much as the writers desired and constantly advocated. Water was often applied by those in charge against our advice and when the available water in the second, third, and fourth feet would have been ample for the needs of the trees for several weeks in advance. At no time during the 18 months while this work was in progress did the moisture percentages in the surface soils drop to the wilting point, and in the third and fourth feet a state of near-saturation was usually maintained. Under these conditions little benefit could be expected from the moisture-control work, and little was actually accomplished. When otherwise healthy trees take on a pale, yellowish color and production drops off, too much water is usually the answer. Especially is this likely to be the case where temperature and plant-food conditions are found to be near the optimum.

Our work on the Yuma Mesa was much more successful. Our advice was usually followed carefully with the result that today they are using successfully less than one-half the water applied formerly. The groves look very much better and the trees are rooting more deeply. Instead of irrigating " by the calendar " every 2 or 3 weeks as was previously the custom, water is now held off for periods of from 5 to 7 weeks, even during the hot summer months, and apparently with beneficial results. The trees here were required to reduce the available water nearly to the wilting point before a succeeding irrigation was given. This is shown by Charts 2 and 3 folded into the back of this bulletin. On the Yuma Mesa we accomplished the main objects of controlled irrigation which are to supply water only when actually needed and in amounts which permit of little waste below the root zone. During the early part of the work some of the trees were allowed to wilt slightly before water was supplied. Following thse tardy irrigations, where the soils had been dried out to the proper point, much fuzzy, new growth of a fine, glossy, green color invariably came out. However, where water was applied too soon, no new growth appeared later. It has been found best to give a heavy irrigation (5 to 6 inches) in basins and then allow the soil to dry down to near the wilting point before giving the next irrigation. The actual amount of water applied at each irrigation will, of necessity, vary with the soil type and can be ascertained only by analysis as the water should not go much below the root zone. Holding off the water as long as possible permits thorough soil-aeration which is of prime importance to successful citrus culture.

Mr. George M. Hill is conducting a very interesting irrigation experiment at the Yuma Mesa Grapefruit Syndicate. About

2½ years ago he divided a very uniform block of 2-year-old grapefruit trees into four equal areas of four rows each. During the summer irrigation periods one area has received a 5-inch irrigation every 2 weeks, one every 4 weeks, one every 6 weeks, and the last every 7 or 8 weeks at which time these latter trees often showed signs of wilting. During the first season the trees receiving the larger amounts of water appeared to grow somewhat faster, the leaves were larger and darker green in color. At the end of the second irrigation season, however, those receiving water every 2 weeks were falling behind the others in rate of growth and were lighter green in color of foliage. The trees irrigated every 4 weeks and every 6 weeks are looking fine, while those receiving the least water are somewhat smaller but show good color. The present summer (1928) is the third year of the experiment. This is a most interesting test and it is hoped that Mr. Hill will continue it for some years to come. It should be stated that, except for irrigation, the entire area has been treated exactly the same in so far as fertilizer and cultural practices are concerned.

Mr. D. C. Aepli, at the Yuma Mesa Orange ranch, is also carrying on an experiment which should be of interest to all owners of old, run-down, chlorotic groves. While large areas of this grove have been replanted during the last 3 years, one 10-acre tract, the "south block," has been spared for investigation. The trees in this block are about 35 years old and a great majority of them were in *very poor* condition before these tests were started. The leaves were light green or yellow in color and the outer ends of all branches were dead back 2 or 3 feet from the tips. Many of the trees had but a few suckers and short branches which carried leaves at all, and these were in the center of the tree around the trunk and were yellow or pale green in color. Very few of the trees bore fruit. It has been Mr. Aepli's practice to withhold water from each tree until the small amount of foliage upon it actually wilted badly, then to throw a basin around it and give a heavy (8- or 10-inch) irrigation. He has thus irrigated the whole 10 acres one tree at a time as it needed it. The entire block has finally been irrigated. It was finished this spring (1928). Many of the trees had received their last irrigation more than 2½ years ago. Now, what happens when these chlorotic, wilted trees are given water? Many of the yellow leaves drop but those which remain become turgid and soon "green up." A large amount of new, green growth quickly "puts out" in the center of the tree, along the old branches and also on the newer wood. After a few months, if the old, dead wood is cut out, a surprisingly green and healthy-looking tree

results. The work at the Yuma Mesa Orange ranch has not yet proceeded to a point where the rejuvenated trees have produced a crop of fruit, so it is not possible at this time to give final details. However, the work thus far looks very promising. A wonderful new growth of leaves has come out this spring on all of these old trees and they all have blossomed heavily. The dead wood has been cut out and the 10-acre block looks better now than it has for *many* years. If the trees carry their fruit through to maturity, a record of yield will be secured.

Viala and Ravac, French viticulturists, have done much experimental work on so-called, lime-induced chlorosis. While they have worked largely with grapevines, some attention has been given to deciduous trees. These French scientists have found that the lime carbonate was much more toxic in the presence of an abundance of water, especially rain water. They explained this by stating that rain water contains much carbonic acid which dissolves the lime carbonate as bicarbonate in which more soluble form it is taken up in larger quantities by the trees. Trees may be entirely yellow during the wet, spring months and later turn a healthy green in June and July after the excess of water has left the ground. They state that poorly drained, calcareous soils almost invariably produce chlorotic plants. They consider the lime to be injurious by preventing proper assimilation of iron, and claim to have greatly improved conditions both by fertilizing and by spraying with iron-sulphate solutions. However, we have not been able to substantiate these claims for citrus.

The chief reason for controlling irrigation is not to save water and labor. It is to build a sturdy, healthy tree which will carry on through the years, bearing profitable crops at a minimum outlay. As stated above, many of the citrus groves in Arizona start off well, but after periods of 10 or 20 years become chlorotic and cease to give remunerative returns. Because of the marked improvement made by citrus trees of all ages where our moisture studies have been made and directions followed, we are in hopes that, when citrus groves are properly cared for otherwise, irrigation control will make for permanent production.

GREENHOUSE WORK

The idea long has been prevalent that calcareous soils in some way tend to produce chlorosis in citrus trees and many think that soils containing much calcium carbonate are absolutely toxic to citrus and should not be used for such plantings. While no very convincing explanation of this phenomenon has been

advanced, some have claimed that a deficiency of iron accompanied by an excess of calcium in the soil solutions of such soils is responsible for the conditions noted. As all of our arable, southern Arizona soils are calcareous, carrying ordinarily from 1 to 6 percent of calcium carbonate, this question is one of considerable importance to our citrus growers. For this reason a series of greenhouse experiments was conducted, growing grapefruit seedlings in pots of washed silica sand to which increasing amounts of calcium carbonate had been added. The objects of the experiment were first, to determine whether calcium carbonate would produce typical chlorosis, and second, if it did, to find whether the chlorotic conditions could be overcome by applications of various kinds of organic matter or by other means.

Late in the fall of 1924 a box of ripe, Clayson grapefruit was obtained from the Heard ranch in the Salt River Valley and the freshly-removed seeds planted in sand in flats in the greenhouse. Moisture and temperature conditions were kept as nearly optimum as possible. On May 1 and 2, 1925, the young seedlings, which were about 2 inches high, were transplanted to pots, five uniform plants to each pot, and placed in the lattice house. A ton of medium fine, silica sand had previously been obtained from Monterey, California, washed with dilute hydrochloric acid to remove all carbonates and finally with distilled water until free from chlorides, and dried. The pots, 12 inches in diameter by 12 inches deep, each received 11 kilograms (about 24 lbs.) of the washed, dry sand. Seven series of eight pots each were prepared, the first five with sand and the last two with Yuma soils. The treatments were as follows:

Series	Pot numbers	Treatments	Irrigated with
1	1 through 8	Sand plus plant foods	Distilled water
2	9 through 16	Sand plus plant foods	Tap water
3	17 through 24	Sand plus 1% $CaCO_3$ plus plant foods	Tap water
4	25 through 32	Sand plus 5% $CaCO_3$ plus plant foods	Tap water
5	33 through 40	Sand plus 10% $CaCO_3$ plus plant foods	Tap water
6	41 through 48	Yuma sand	Tap water
7	49 through 56	Yuma silt	Tap water

Chemically pure, precipitated calcium carbonate was carefully mixed with the sand as indicated above. The tap water was free from carbonates but carried about 50 p.p.m. of soluble calcium as sulphate. Once each week the pots were watered with measured amounts of a complete nutrient solution sufficient to supply all plant-food requirements.* At first it was found

* Iron was supplied as ferric tartrate.

Fig. 3.— Grapefruit seedlings grown in washed sand with different organic materials.

Fig. 4.— Grapefruit seedlings grown in washed sand plus 1 percent calcium carbonate and different organic materials.

Fig. 5. — Grapefruit seedlings grown in washed sand plus 5 percent calcium carbonate and different organic materials.

Fig. 6. — Grapefruit seedlings grown in washed sand plus 10 percent calcium carbonate and different organic materials.

necessary to water the pots every other day and, in order to lessen evaporation during the months of May, June, and July, pads of cotton were placed on the surface of the pots. All of the plants grew well except those treated with the larger amounts of calcium carbonate. These soon became chlorotic. Later the seedlings receiving the 1-percent treatment and also those growing in the Yuma sand (3% $CaCO_3$) lost color to some extent.

On August 18, when most of the plants were about 4 inches high, recuperative measures were attempted. One pot in each series was treated as follows:

No. 1. 150 grams dried and ground peat in surface-inch.

No. 2. 150 grams dried and ground muck in surface-inch.

No. 3. 25 grams rotted, dried, and ground alfalfa in surface-inch.

No. 4. 100 cc. each week of a 0.1% solution ferric tartrate.

The other four pots of each series were left untreated as checks. On October 21, but slight improvement had been shown by the plants in any of the treated pots, although those receiving peat and muck were somewhat greener in color. This was quite marked in the 1-percent, calcium-carbonate-treated series and in th Yuma-sand series. Apparently the seedlings had been allowed to become too chlorotic before recuperative measures were attempted. Therefore, it was decided to repeat the experiment the following year, adding the organic materials at the time of planting rather than later after chlorosis had taken place.

During the second week in April, 1926, the second experiment was started by transplanting another lot of young grapefruit seedlings into the same seven series of pots as had been used the previous year. About a week before planting, the contents of each pot had been removed, thoroughly mixed and the materials indicated below incorporated into the surface 3 or 4 inches:

Pot 1 of each series received 150 grams of dry, ground peat.

Pot 2 of each series received 150 grams of dry, ground muck.

Pots 3 and 4 of each series received 150 grams of dry, ground alfalfa.

Pots 5 and 6 of each series received 150 grams of dry, ground manure.

Pots 7 and 8 of each series received nothing (checks).

The pots were watered with tap water. The first few weeks' growth was slow due to unusually cold weather, but later normal development resulted. About the middle of July the plants were

thinned to three per pot. On July 20 and thereafter, pots 3, 5, and 7 of each series were watered with a diluted manure extract, the others receiving tap water as previously. In all series, the peat and muck produced the best plants and, with the exception of those pots carrying 10 percent calcium carbonate, little chlorosis was noted where either of these two materials was used. On November 1 the plants were removed from the pots and the roots carefully washed free from the sand or soil. The three seedlings grown in each pot were usually uniform both in size and appearance. Representative plants from each of the treatments were photographed and appear in figures 3, 4, 5, and 6. These were the ones watered with tap water. The seedlings receiving the manure extract showed little improvement, if any, over those watered with tap water. Figure 3 shows the plants grown in washed sand only; figure 4 with 1-percent calcium carbonate; figure 5 with 5-percent calcium carbonate, and figure 6 with 10-percent calcium carbonate. Plant No. 1 in each figure received the peat; No. 2, the muck; No. 3, the alfalfa; No. 4, the manure, and No. 5 was untreated. Unfortunately the photographs do not show the color of the foliage. In all cases the plants at the left which received peat or muck were a darker green while those at the right were lighter in color. Plant No. 5 in each series was very yellow, indicating a chlorotic condition. These representative seedlings were dried out in the oven at 100° C. and the dry weights in grams recorded in Table XII.

A perusal of the figures and the data presented in Table XII indicates that, in the case of grapefruit seedlings organic materials especially peat and muck, largely are able to overcome the deleterious effects of moderate amounts of calcium carbonate when present in the substratum, notwithstanding the fact that, at this age, the plants are especially delicate and readily susceptible to adverse, external conditions. From these results we cannot argue definitely that calcium carbonate in soils well supplied with organic matter will never become injurious to grapefruit trees as they mature and bear year after year, but it certainly appears that this may well be the case where the organic-matter content of the soil is properly maintained and the percentages of calcium carbonate are not excessive.

Figure 7 shows two grapefruit seedlings of the same age as those shown in the other cuts. Number 1 was grown in Yuma sand and No. 2 in the Yuma silt, both of which had received a small top-dressing of peat. The plants showed a dark green, healthy color.

Fig. 7.— Grapefruit seedlings grown in Yuma sand (1) and Yuma silt (2) both receiving peat.

TABLE XII.— DRY WEIGHTS OF GRAPEFRUIT SEEDLINGS GROWN IN THE PRESENCE OF INCREASING AMOUNTS OF CALCIUM CARBONATE PLUS DIFFERENT ORGANIC MATERIALS.

Series	Calcium carbonate percent	Organic material (150 grams per pot)				
		Peat	Muck	Alfalfa	Manure	None
1	0	1.33	1.00	0.75	0.75	0.62
2	1	0.95	1.00	0.50	0.60	0.60
4	5	1.00	0.87	0.65	0.50	0.50
3	10	0.80	0.90	0.60	0.60	0.32

SUMMARY AND CONCLUSIONS

For the past 8 or 10 years many of the older citrus groves in the Salt River Valley and on the Yuma Mesa have been deteriorating both in yield and in quality of fruit produced. The leaves have become chlorotic, the set of fruit is small and in many cases much dead and weak wood is in evidence. As the poor conditions noted have been brought about, not by organic diseases, but apparently by a general physiological derangement of the trees, the work reported in this bulletin was done in an endeavor to find whether certain soil treatments might not be of value either in preventing a further decline, or in actually improving present conditions. For convenience the work was divided into four parts: the laboratory studies on the soils in question, the fertilizer studies in the field, the moisture-control work in the field, and the pot-culture work in the greenhouses at Tucson.

The laboratory work on the soils included mechanical, chemical, and bacteriological studies. They showed the soils to be free from toxic concentrations of the alkali salts, but fairly high in calcium carbonate and alkaline in reaction (pH 8.1 to 8.5). Total nitrogen was low in all cases but its availablity was high. Both total and available (replaceable) potash were high. Total phosphoric acid was fairly high but its availability was slight. Taken as a whole, the bacteriological studies indicated a fair degree of microbiological activity. Nitrogen fixation was especially high. A brief account of the importance of bacteria to soil fertility is given. Certain soil-solution studies are also reported together with results from the use of various salts as clay coagulants. The mechanical analyses and soil profiles of the important citrus soil types are discussed. From this laboratory work, it appeared that organic matter, nitrogen, and soluble phosphates should be of value on the soils in question.

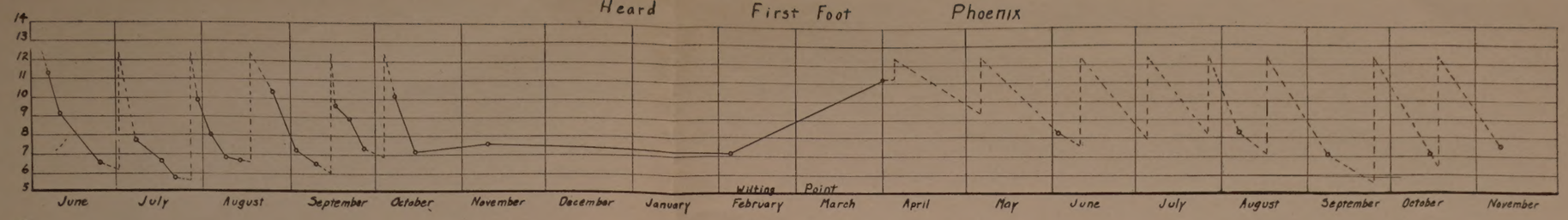
The fertilizer- and soil-amendment studies were conducted in 8 or 10 of the poorer groves, both in the Salt River Valley and on the Yuma Mesa. Both surface applications and "deep treatments" were included. A detailed discussion of this work is given. Although a slight improvement was usually shown where both manure and double-superphosphate were applied deeply, the results of the fertilizer treatments appeared to be largely negative. Spraying the chlorotic foliage with ferrous sulphate and manganese sulphate also was without permanent effect.

The field moisture-control work was extremely successful. A general discussion of soil moisture together with the methods used and the results secured in the control work are given in some detail. Where the irrigation program was changed to con-

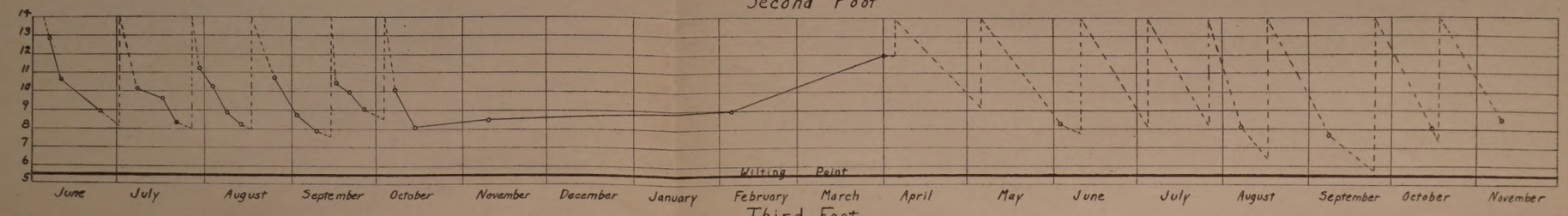
form to the information secured from the soil-moisture studies, a remarkable recovery usually took place. After 1 or 2 years of work, several of the older chlorotic groves appear to be well on their way towards profitable production. It appears best to give a heavy irrigation (5 or 6 inches) in basins and then allow the soil to approach closely the wilting point before another irrigation is given. This gradual drying-out between irrigations permits of thorough soil aeration, which is of great importance in citrus culture.

Pot-culture work with grapefruit seedlings in the greenhouse showed that excessive amounts of calcium carbonate in the substratum caused chlorosis but that this condition could be alleviated to a large extent by the application of organic materials. Peat and muck gave best results followed by alfalfa and manure.

Heard First Foot Phoenix


Wilting Point
June July August September October November December January February March April May June July August September October November

Second Foot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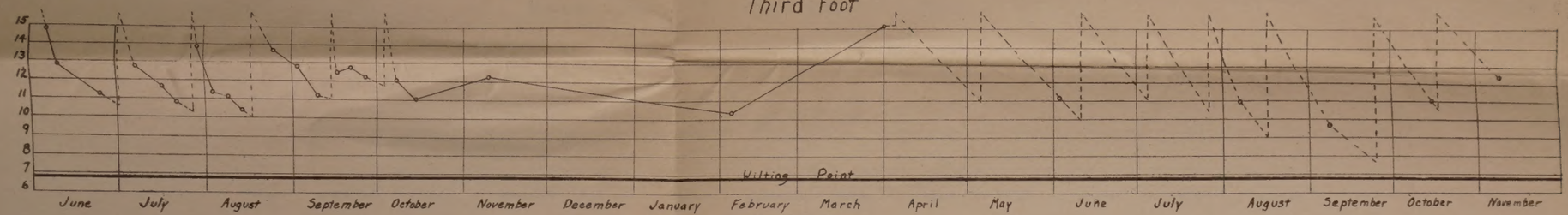
Third Foot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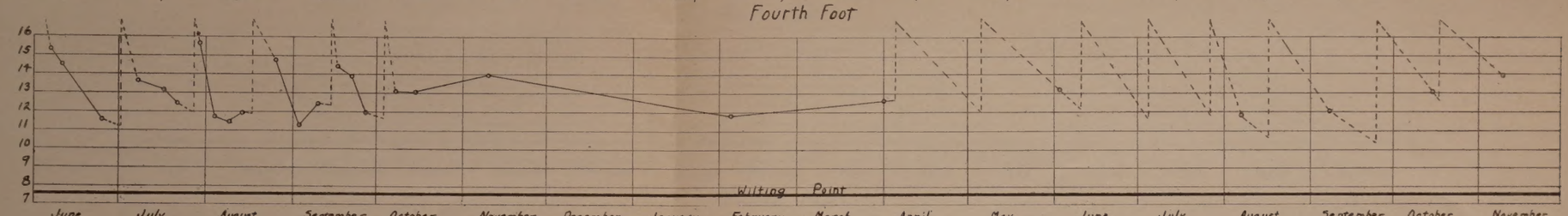
Wilting Point
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Thompson First Foot Phoenix

Wilting Point
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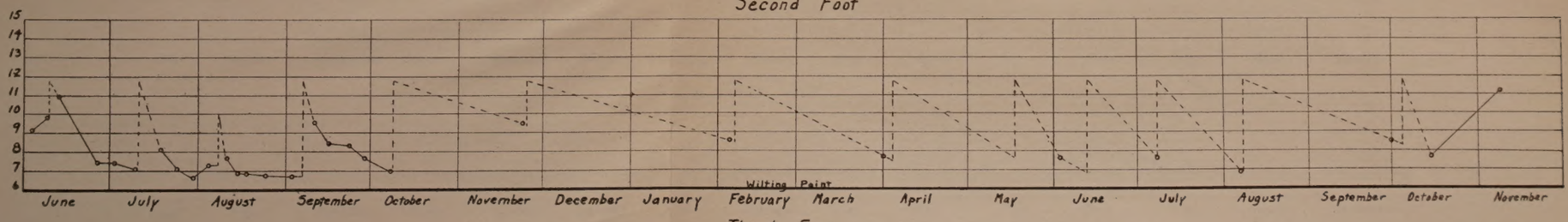
Second Foot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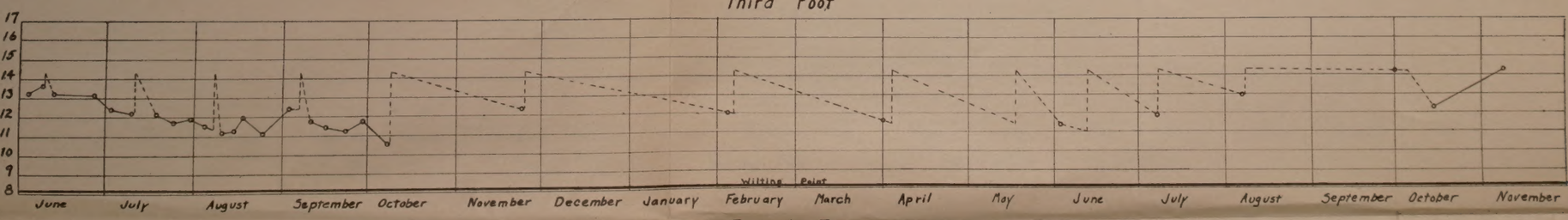
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Fourth Foot

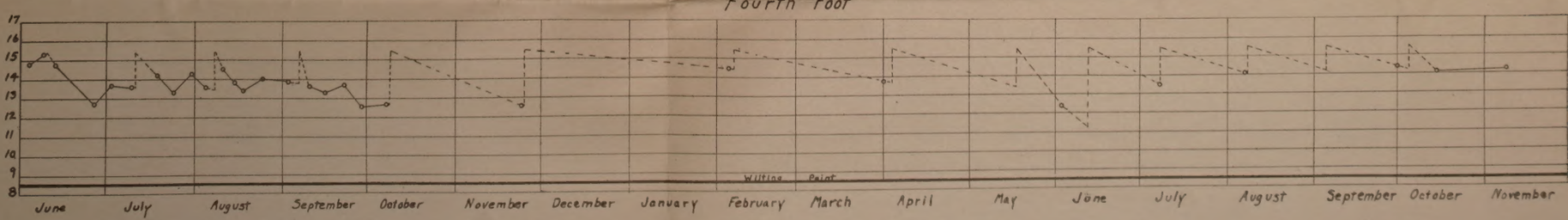
Wilting Point
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Chart 1. Moisture Control in Salt River Valley Groves.

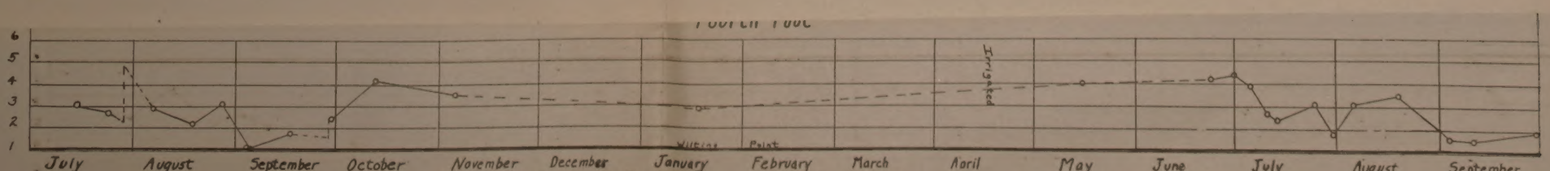
Irrigated
Wilting Point
July August September October November December January February March April May June July August September

Chart 2. Moisture Control in Yuma Mesa Groves.